



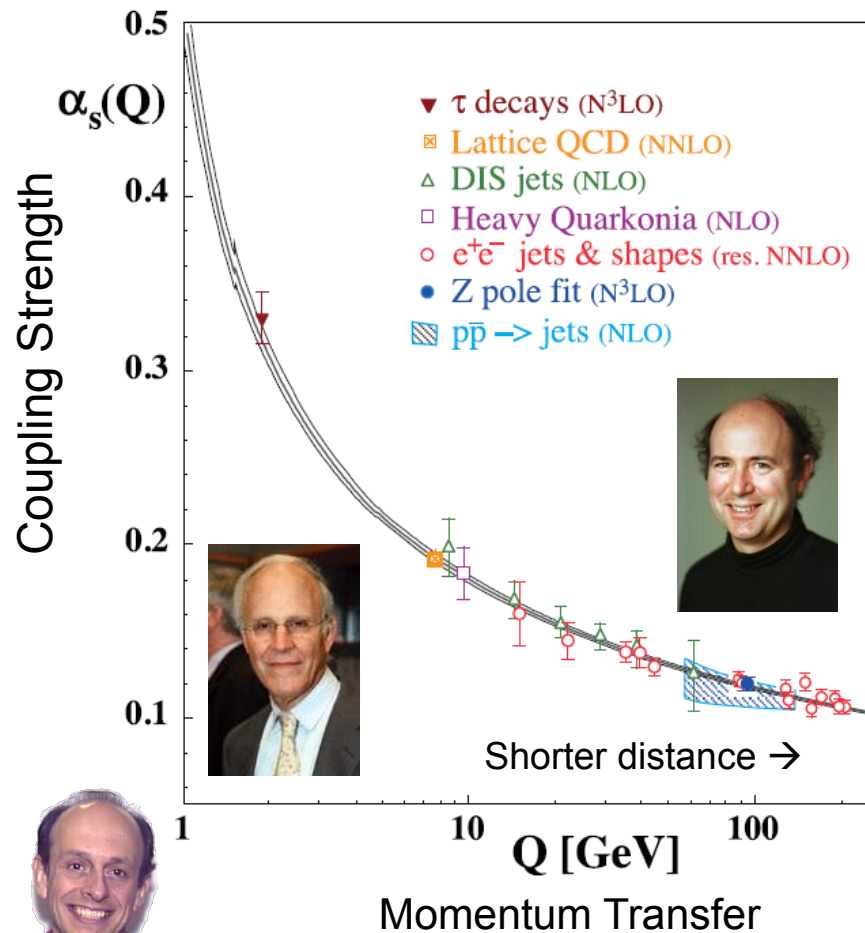
Introduction to the EIC and eSTAR program



Ming Shao (USTC)

Salient Feature of Strong Interaction

Asymptotic Freedom

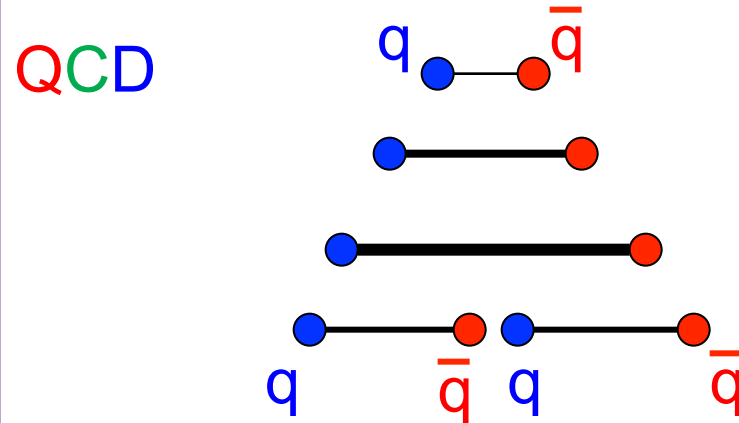


Wilczek, Gross, and Politzer

Quark Confinement

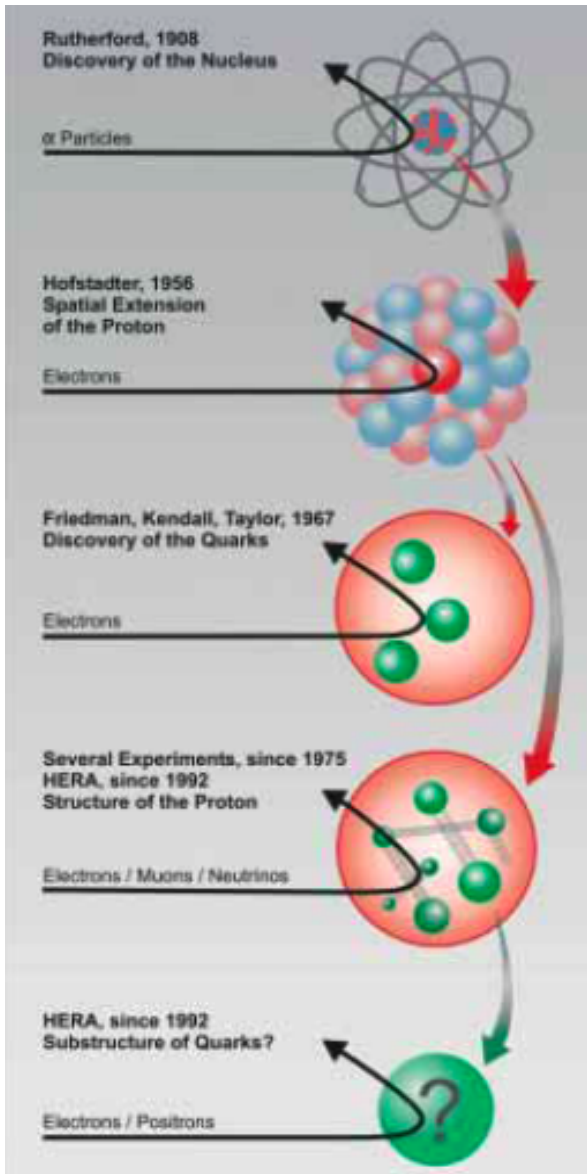
一尺之棰，日取其半，万世不竭
- 庄子 (~ 300 BC)

Take half from a foot long stick each day,
You will never exhaust it in million years.

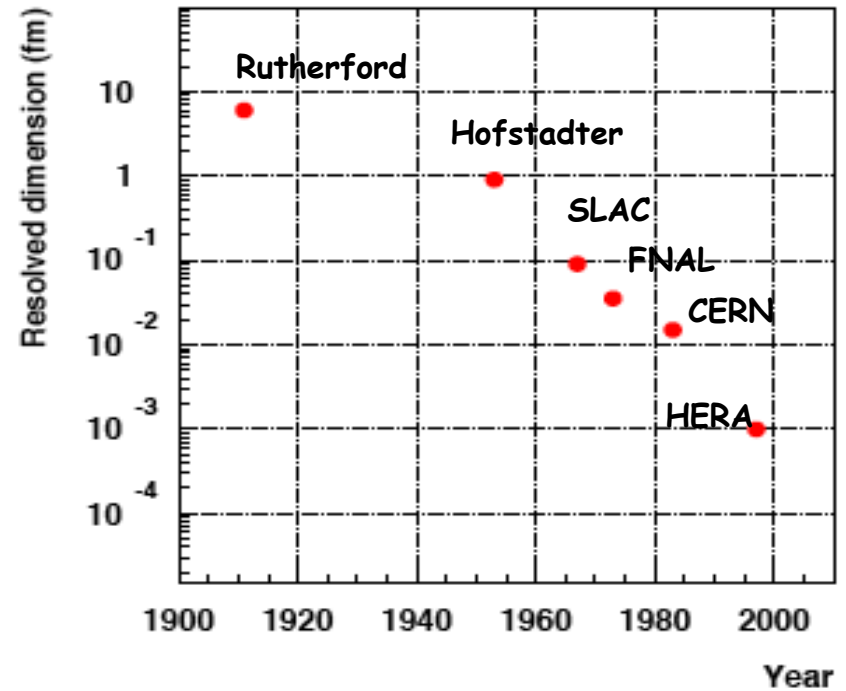


Quark pairs can be produced from vacuum
No free quark can be observed

General considerations on scattering experiments

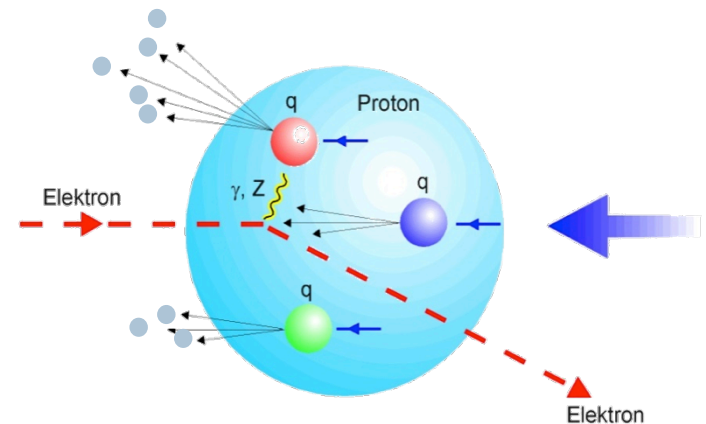


Probing smaller distances requires larger momentum transfer (small wavelength)



Scatter point-like **probe** onto object (**target**)

Measurement of the final-state (e.g. scattered **electron**):
⇒ Structure of **target**!



Exploring proton/nuclear structure

Elastic electron-proton/nucleus scattering

- Scattering of electron (Spin 1/2) on point-charge charge (Spin 0): Mott cross-section

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott}^* = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} \cdot \cos^2(\theta/2)$$

- Take into account finite charge distribution:
Form factor

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}^* \cdot |F(q^2)|^2$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}^* \frac{E'}{E}$$

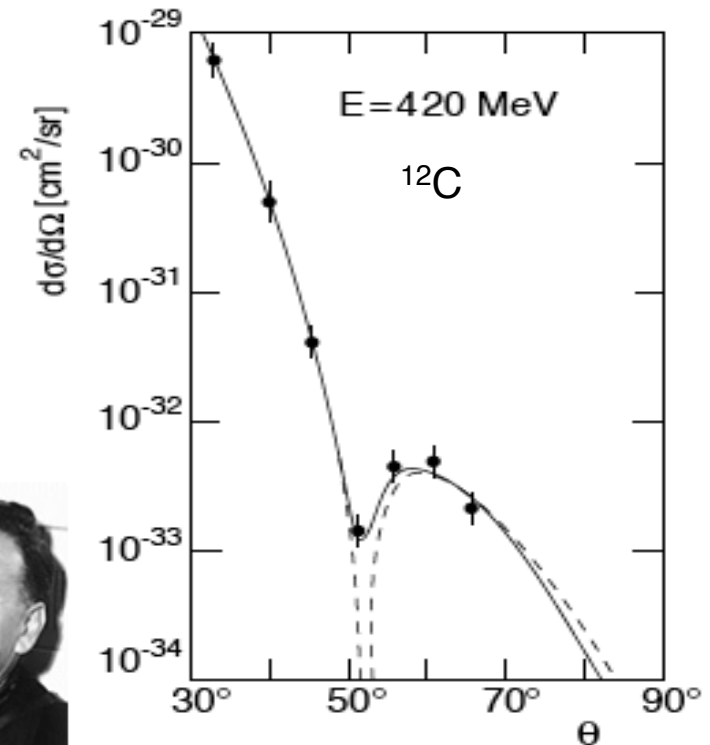
- Theoretically (scattering process $2 \rightarrow 2$),

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{\hbar E'}{8\pi M c E}\right)^2 \langle |\mathcal{M}|^2 \rangle$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \frac{4\alpha^2 E'^2}{q^4}$$

$$q^2 = -4(E/c)(E'/c)\sin^2(\theta/2)$$

E, E' – electron energy before/after scattering

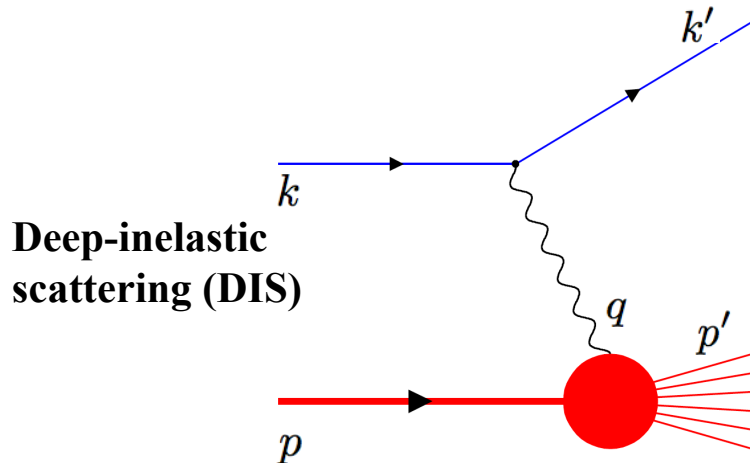


Hofstadter, 1953

Exploring the Proton Partonic Structure

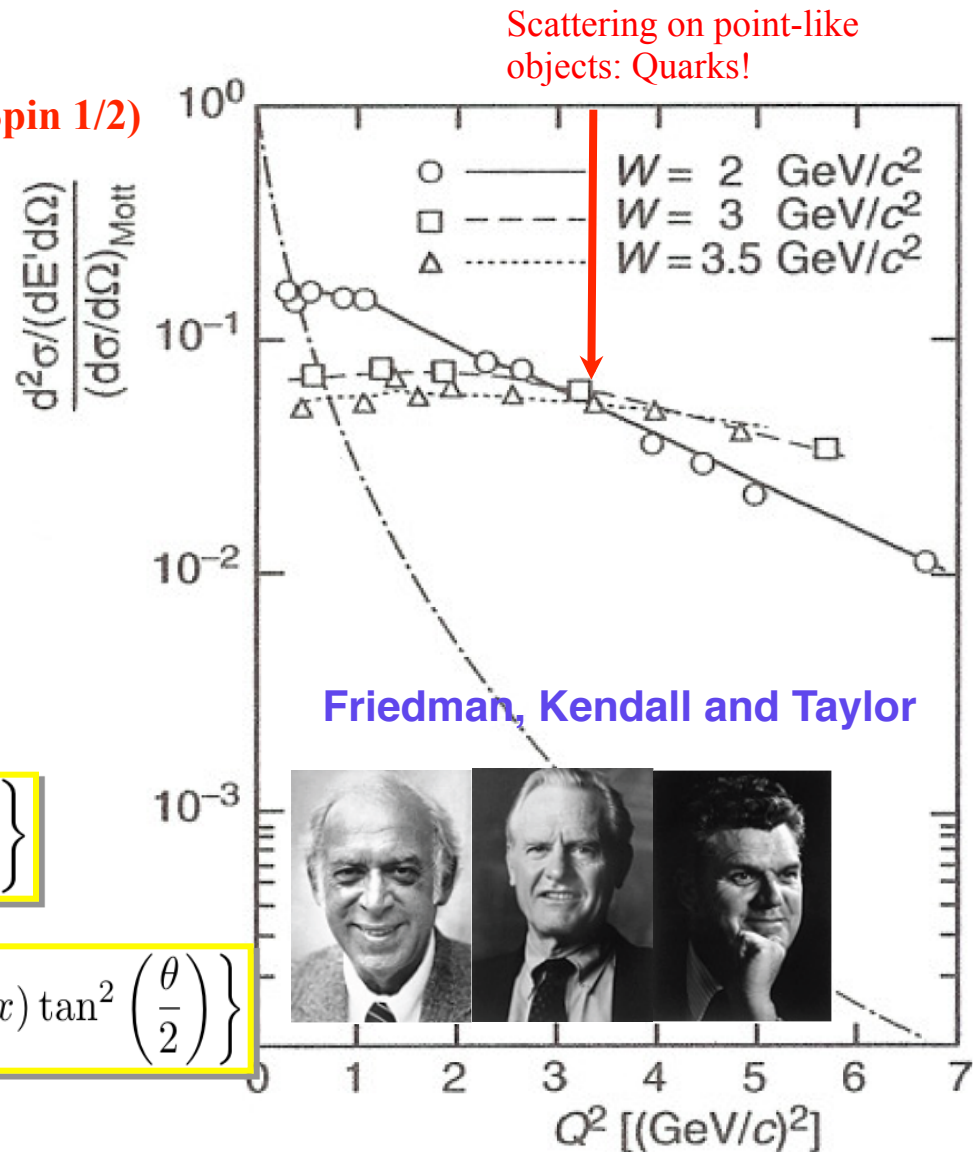
Inelastic e+p scattering

- Scattering of electron (Spin 1/2) on proton (Spin 1/2)



$$\left(\frac{d\sigma}{d\Omega} \right) = \left(\frac{d\sigma}{d\Omega} \right)_{Mott} \frac{E'}{E} \left\{ 1 + 2\tau \tan^2 \left(\frac{\theta}{2} \right) \right\}$$

$$\left(\frac{d^2\sigma}{dE'd\Omega} \right) = \left(\frac{d\sigma}{d\Omega} \right)_{Mott} \left\{ W_2(Q^2, x) + 2W_1(Q^2, x) \tan^2 \left(\frac{\theta}{2} \right) \right\}$$



DIS Kinematic Variables

$$Q^2 = -(k - k')^2 = -(p - p')^2 = -t = -q^2$$

(momentum transfer)² virtuality of γ^* , Z^0 , $W^\pm \Rightarrow$ ("size" of the probe)⁻¹

$$x = \frac{Q^2}{2(p \cdot q)} \simeq -\frac{t}{u+s} \quad 0 \leq x \leq 1$$

fraction of the proton momentum carried by the charged parton

$$y = \frac{p \cdot q}{p \cdot k} \simeq \frac{u+s}{s} \quad 0 \leq y \leq 1$$

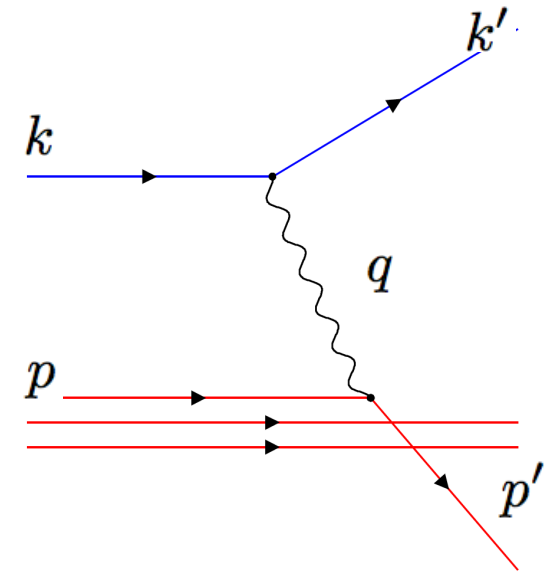
fraction of the electron energy carried by the virtual photon
("inelasticity")

$$s = (k + p)^2 \simeq 4E_e E_P \quad Q^2 \simeq s \cdot x \cdot y$$

center of mass energy of ep system

$$W^2 = (p + q)^2 = (p')^2 = m_p^2 + \frac{Q^2}{x}(1 - x) \simeq s + t + u$$

(mass)² of $\gamma^* p$ system



There are more variables ...

Structure Functions

- Structure function measurement: Formalism

- In terms of laboratory variables:

$$\left(\frac{d^2\sigma}{dE'd\Omega} \right) = \left(\frac{d\sigma}{d\Omega} \right)_{Mott} \left\{ W_2(Q^2, x) + 2W_1(Q^2, x) \tan^2 \left(\frac{\theta}{2} \right) \right\}$$

- Formulate this now in relativistic invariant quantities:

$$\theta'_e, \quad E'_e \rightarrow y_e, \quad Q_e^2$$

- Instead of W_1 and W_2 , use: F_1 and F_2 :

$$F_1 = m_p W_1$$

$$F_2 = \nu W_2 \quad \nu = q \cdot p / M = ys / (2M)$$

Longitudinal structure function: F_L

$$\left(\frac{d^2\sigma}{dydQ^2} \right) = \frac{2\pi\alpha^2 Y_+}{yQ^4} \left(F_2 - \frac{y^2}{Y_+} F_L \right)$$

$$F_L = F_2 - 2xF_1$$

$$Y_+ = 1 + (1 - y)^2$$

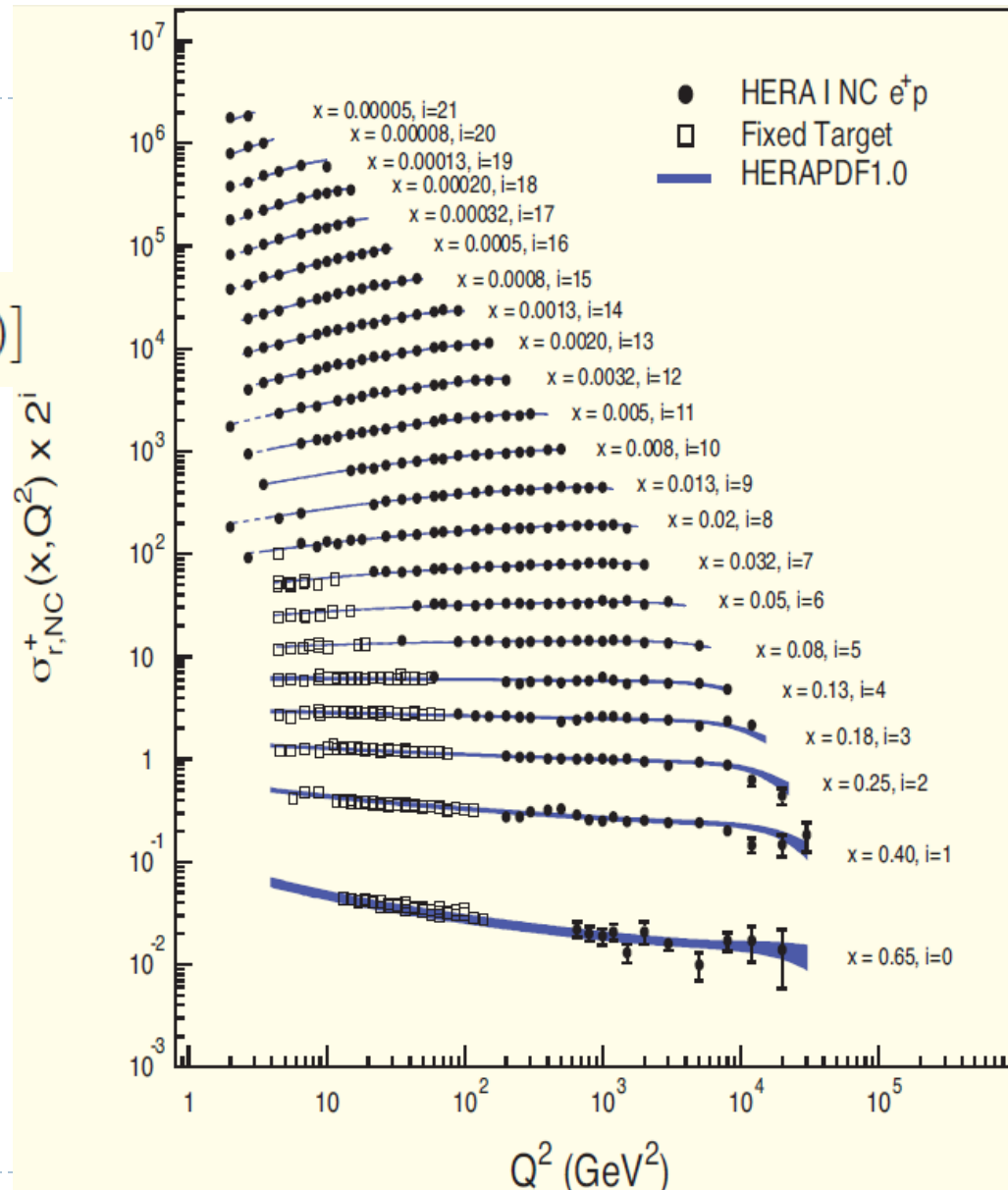
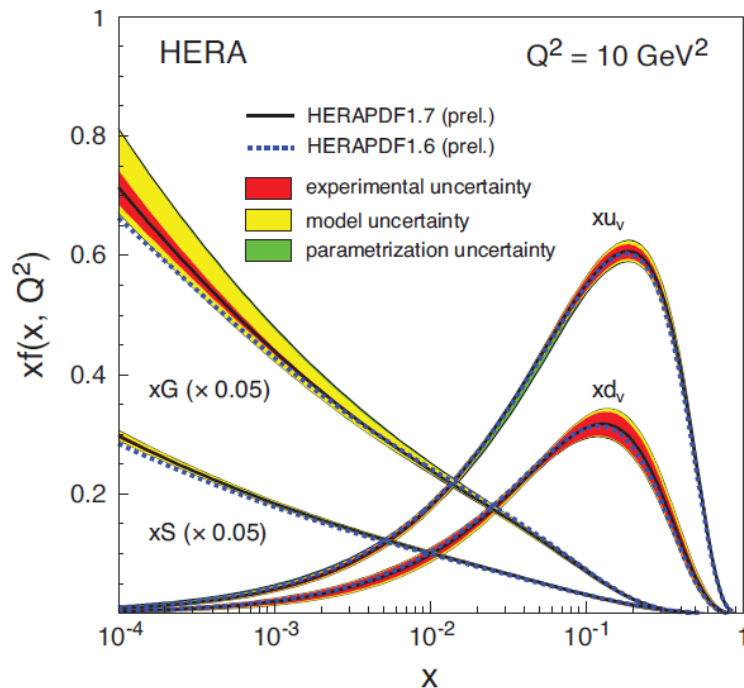
Parton Distribution Function (PDF)

$$\sigma_r = \left(\frac{d^2\sigma}{dx dQ^2} \right) \frac{xQ^4}{2\pi\alpha^2[1 + (1-y)^2]}$$

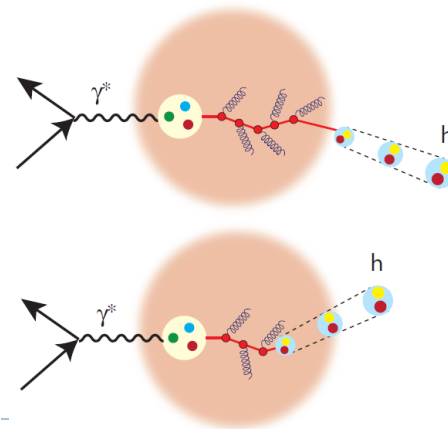
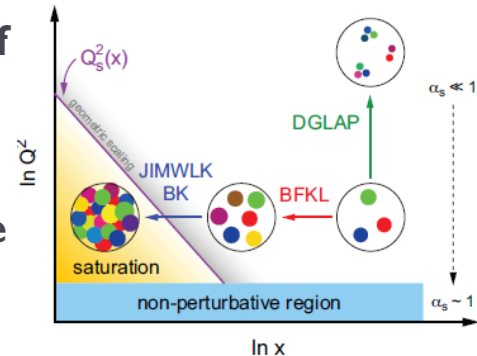
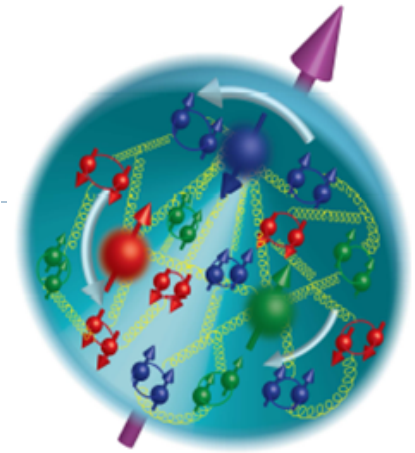
$$= F_2(x, Q^2) - \frac{y^2}{1 + (1-y)^2} F_L(x, Q^2)$$

$$F_2(x, Q^2) = x \sum e_q^2 [q(x, Q^2) + \bar{q}(x, Q^2)]$$

At large Q^2 and to leading order (LO)



Open questions



► How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

- How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction?
- What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?

► Where does the saturation of gluon densities set in?

- Is there a simple boundary that separates this region from that of more dilute quark-gluon matter?
- If so, how do the distributions of quarks and gluons change as one crosses the boundary?
- Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

► How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

- How does the transverse spatial distribution of gluons compare to that in the nucleon?
- How does nuclear matter respond to a fast moving color charge passing through it?
- Is this response different for light and heavy quarks?

An EIC is needed!

Why EIC?

An EIC is the ultimate machine to provide answers to these questions for the following reasons:

1. A **collider** is needed to provide kinematic reach well into the gluon-dominated regime;
2. **Electron beams** are needed to bring to bear the unmatched precision of the electromagnetic interaction as a probe;
3. **Polarized nucleon beams** are needed to determine the correlations of sea quark and gluon distributions with the nucleon spin;
4. **Heavy ion beams** are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charges in nuclear matter.

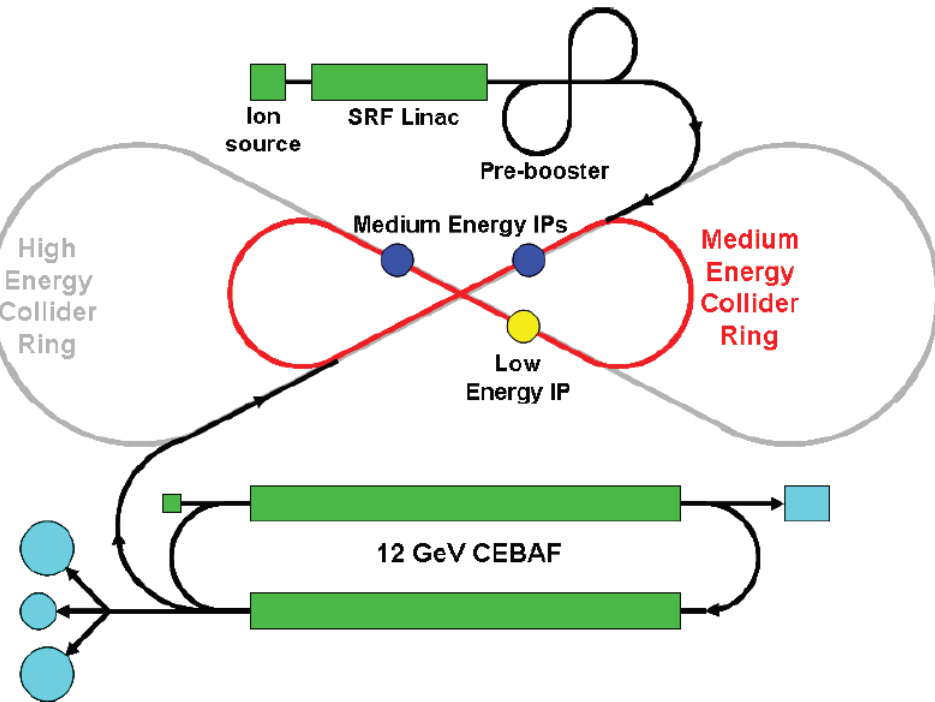
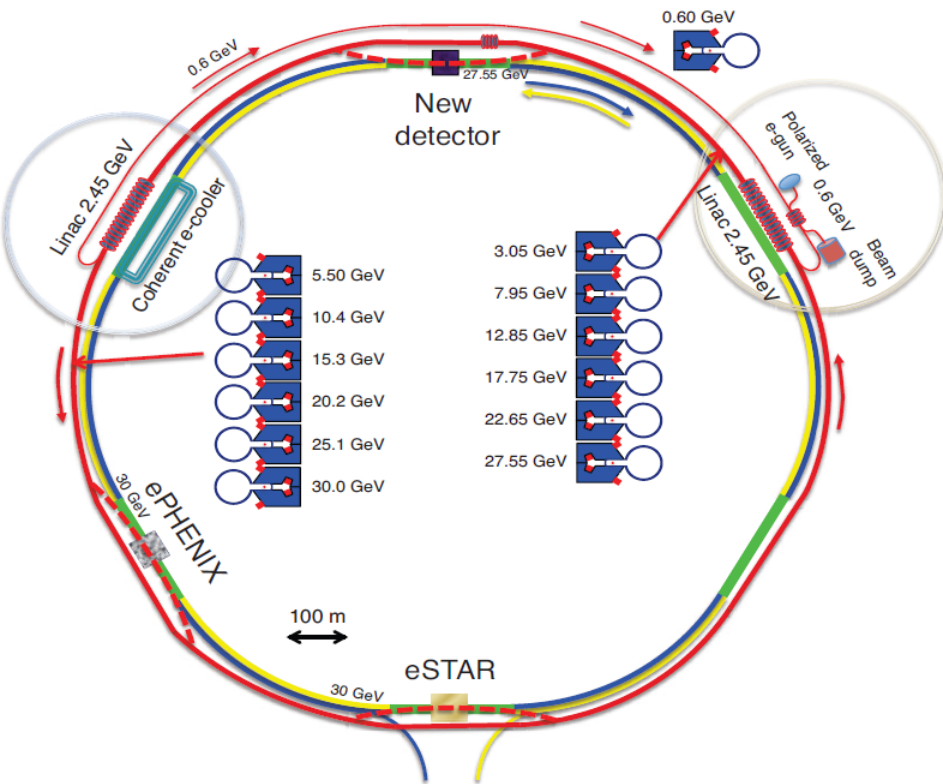
The EIC design exceeds the capabilities of HERA, the only electron-proton collider to date, by adding

- a) polarized proton and light-ion beams;
- b) a wide variety of heavy-ion beams;
- c) 2~3 orders of magnitude increase in **luminosity** to facilitate tomographic imaging;
- d) wide energy variability to enhance the sensitivity to gluon distributions.

Realization of an EIC

The EIC machine designs are aimed at achieving:

1. Highly polarized ($\sim 70\%$) electron and nucleon beams
2. Ion beams from deuteron to the heaviest nuclei (uranium or lead)
3. Variable center of mass energies from ~ 20 to ~ 100 GeV, upgradable to 150 GeV
4. High collision luminosity $10^{33} \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
5. Possibilities of having more than one interaction region



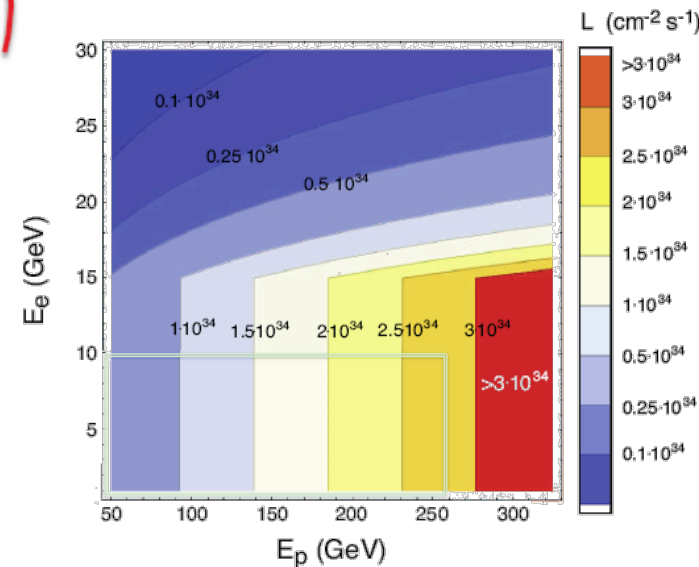
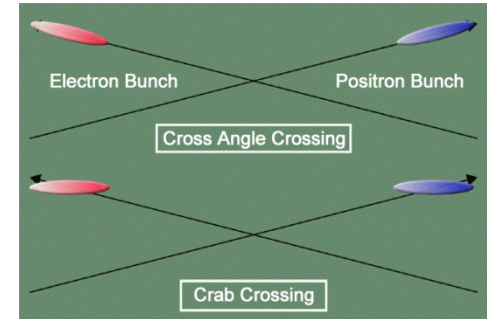
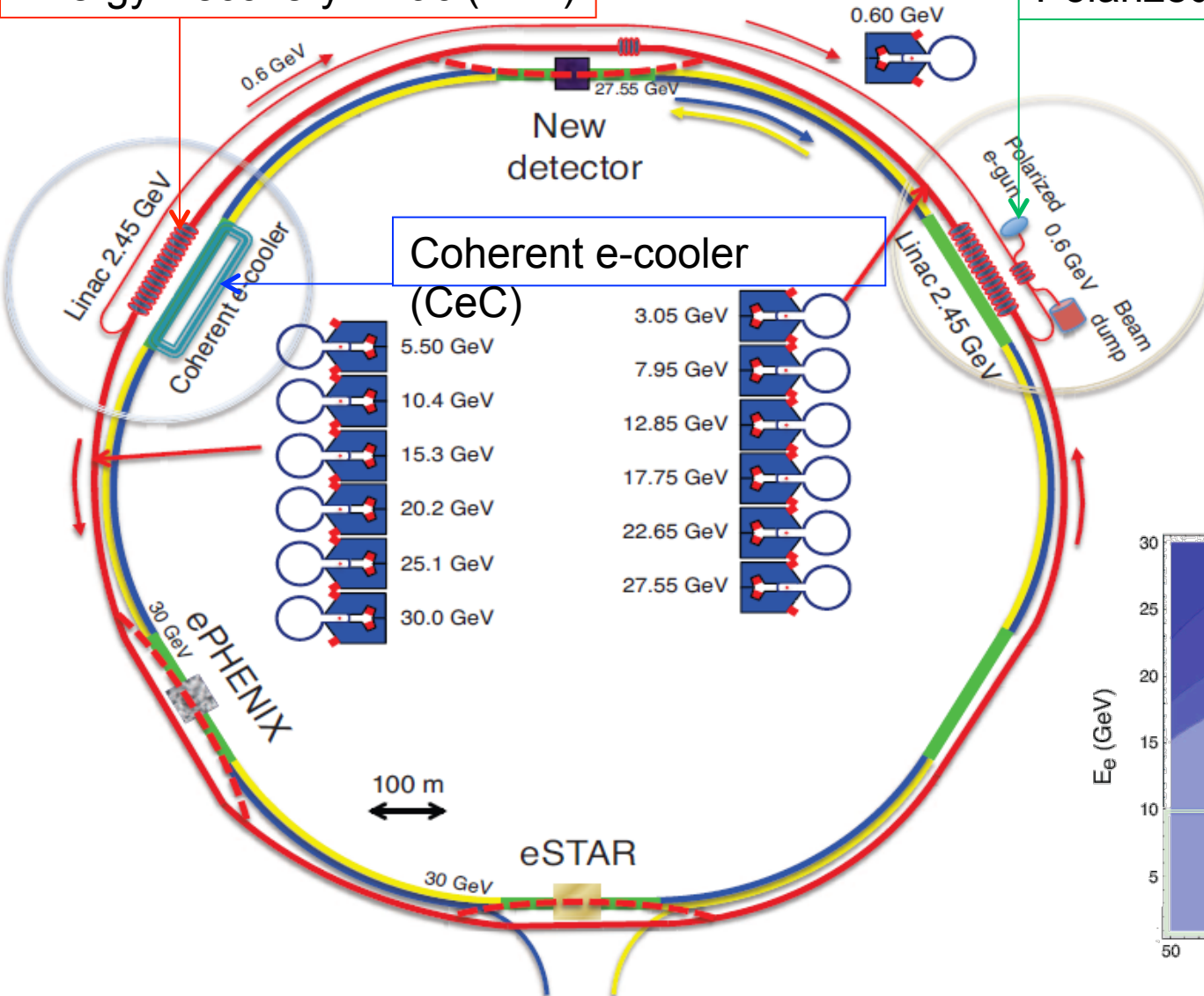
MEIC/ELIC

eRHIC

eRHIC

Energy Recovery Linac (ERL)

Polarized e-gun



The Spin and Flavor Structure of the Nucleon

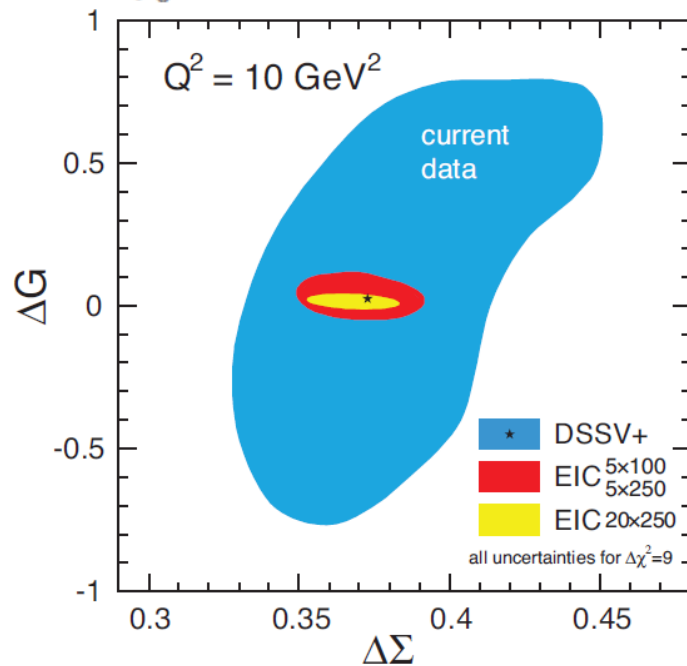
$$\Delta f(x, Q^2) \equiv f^+(x, Q^2) - f^-(x, Q^2)$$

$$\frac{1}{2} = S_q + L_q + S_g + L_g$$

$$S_q(Q^2) = \frac{1}{2} \int_0^1 \Delta \Sigma(x, Q^2) dx$$

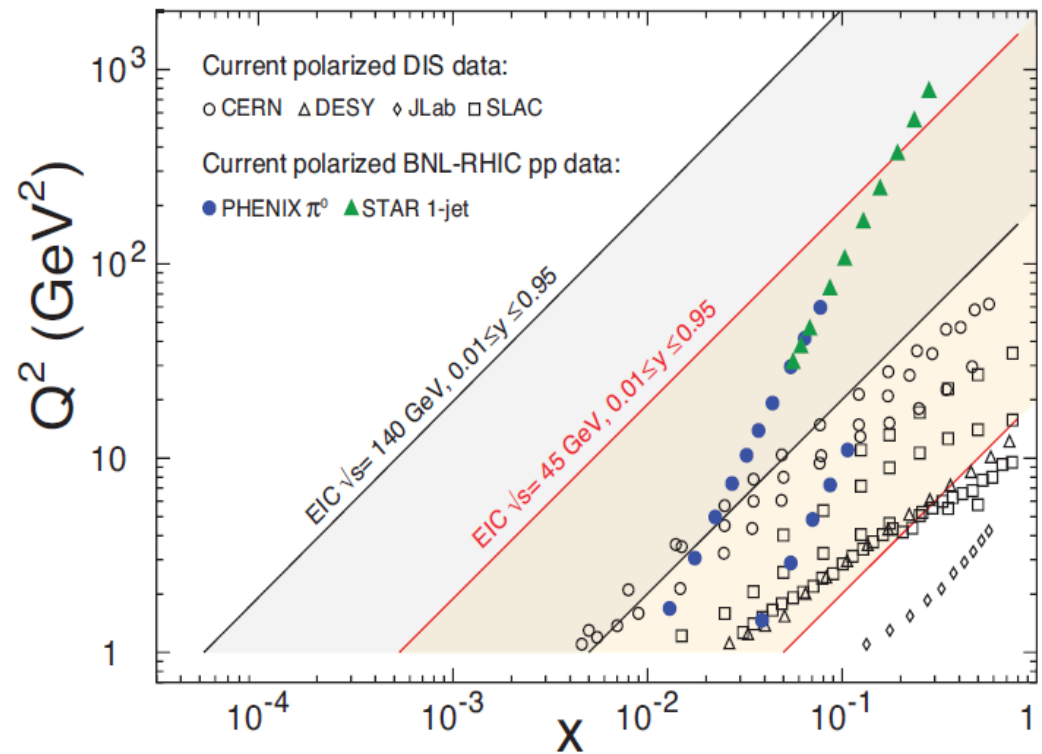
$$\equiv \frac{1}{2} \int_0^1 (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s})(x, Q^2) dx$$

$$S_g(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$

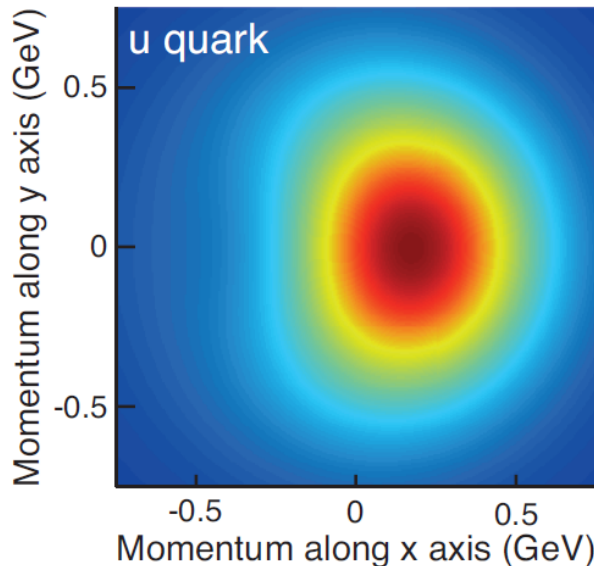


$$\frac{1}{2} \left[\frac{d^2 \sigma^{\rightarrow\rightarrow}}{dx dQ^2} - \frac{d^2 \sigma^{\rightarrow\leftarrow}}{dx dQ^2} \right] \simeq \frac{4\pi \alpha^2}{Q^4} y(2-y) g_1(x, Q^2)$$

$$g_1(x, Q^2) = \frac{1}{2} \sum e_q^2 [\Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2)]$$

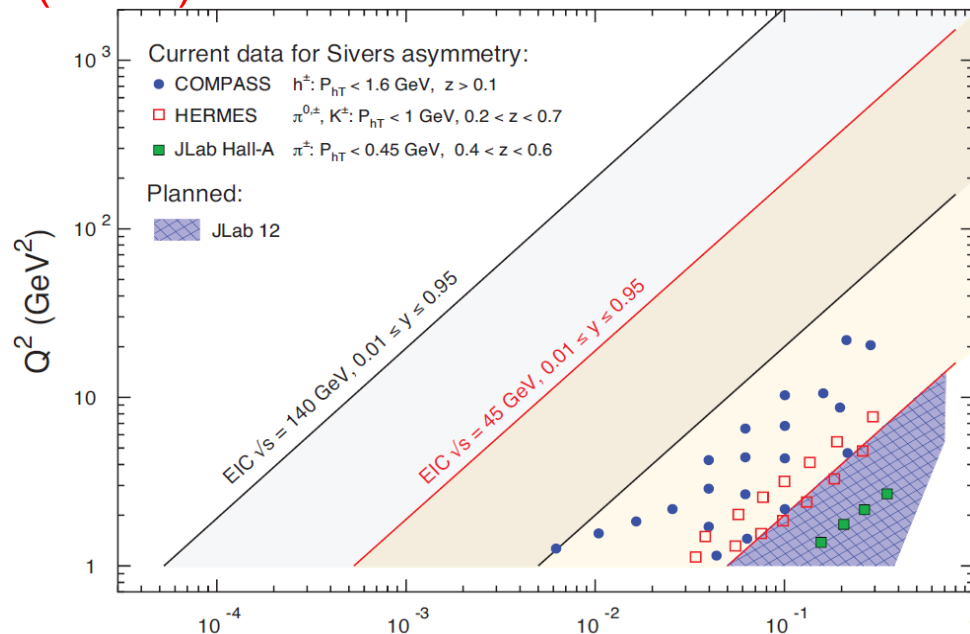


The Confined Motion of Partons Inside the Nucleon



The density in the transverse-momentum plane for unpolarized quarks with $x = 0.1$ in a nucleon polarized along the y direction.

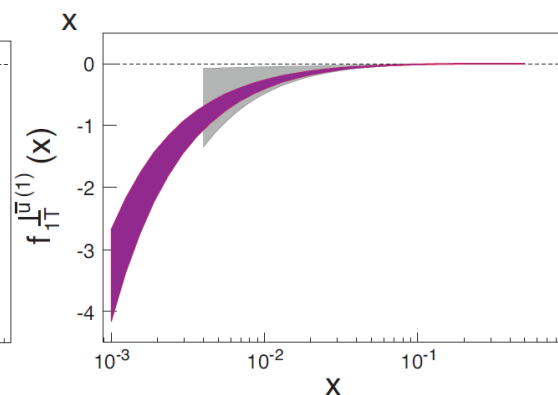
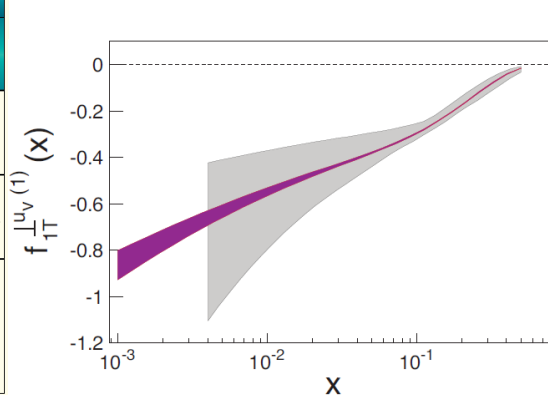
Transverse momentum dependent (TMD) quark distributions can be accessed by **semi-inclusive DIS (SIDIS)**



Leading Twist TMDs



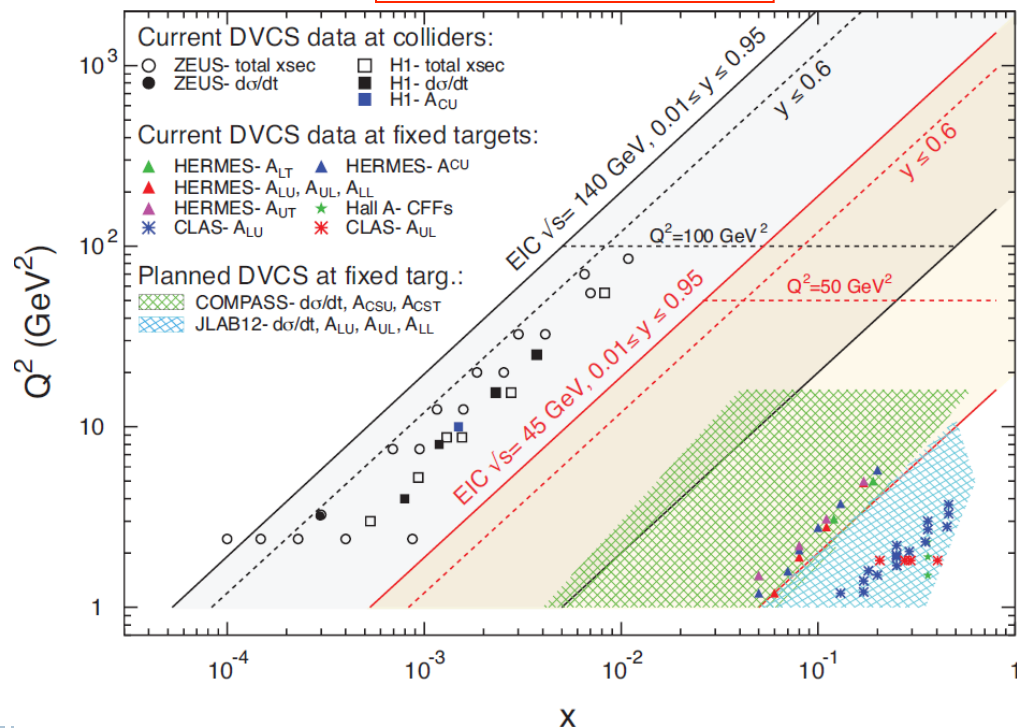
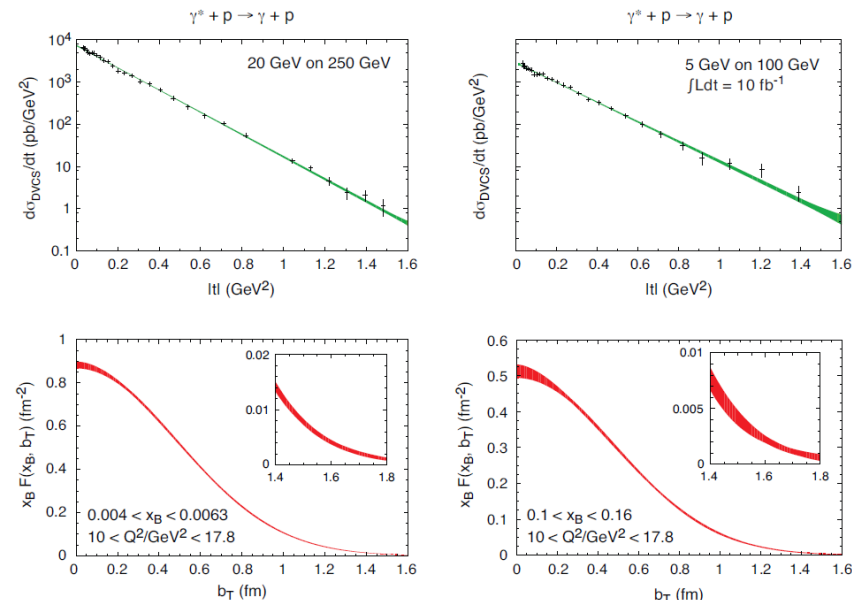
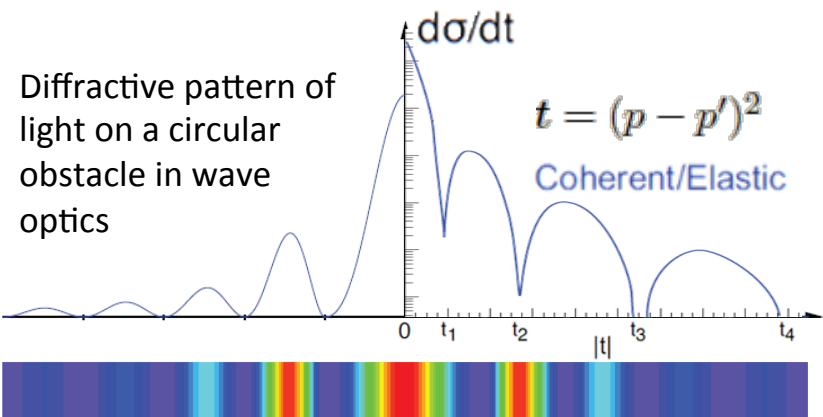
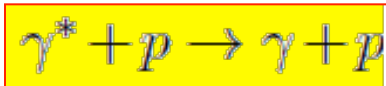
| | | Quark Polarization | | |
|----------------------|---|-------------------------|------------------------------|-------------------------------|
| | | Un-Polarized (U) | Longitudinally Polarized (L) | Transversely Polarized (T) |
| Nucleon Polarization | U | $f_1 =$ | | $h_1^\perp =$ Boer-Mulders |
| | L | | $g_{1L} =$ Helicity | $h_{1L}^\perp =$ |
| | T | $f_{1T}^\perp =$ Sivers | $g_{1T}^\perp =$ | $h_{1T}^\perp =$ Transversity |



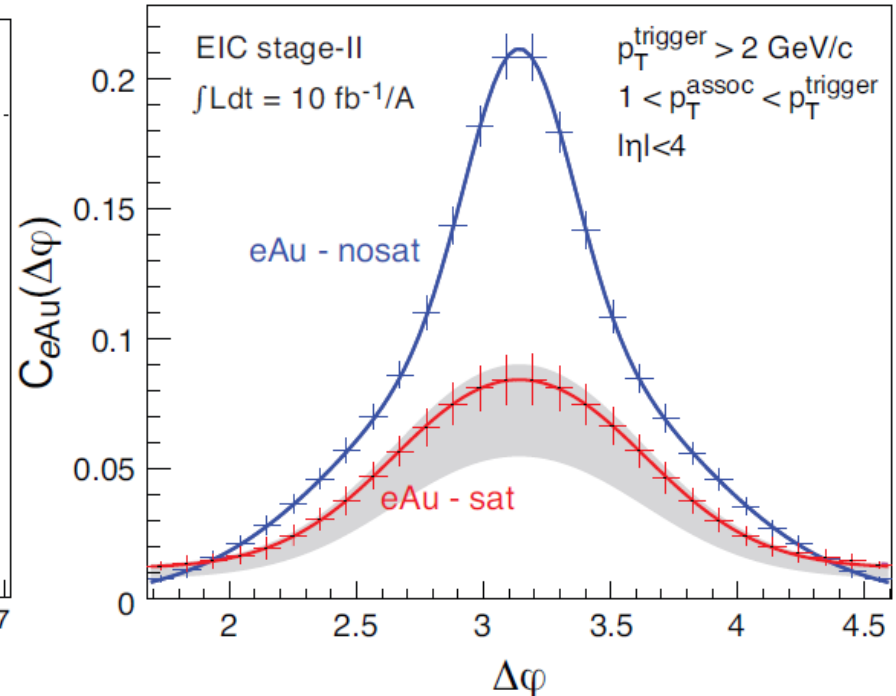
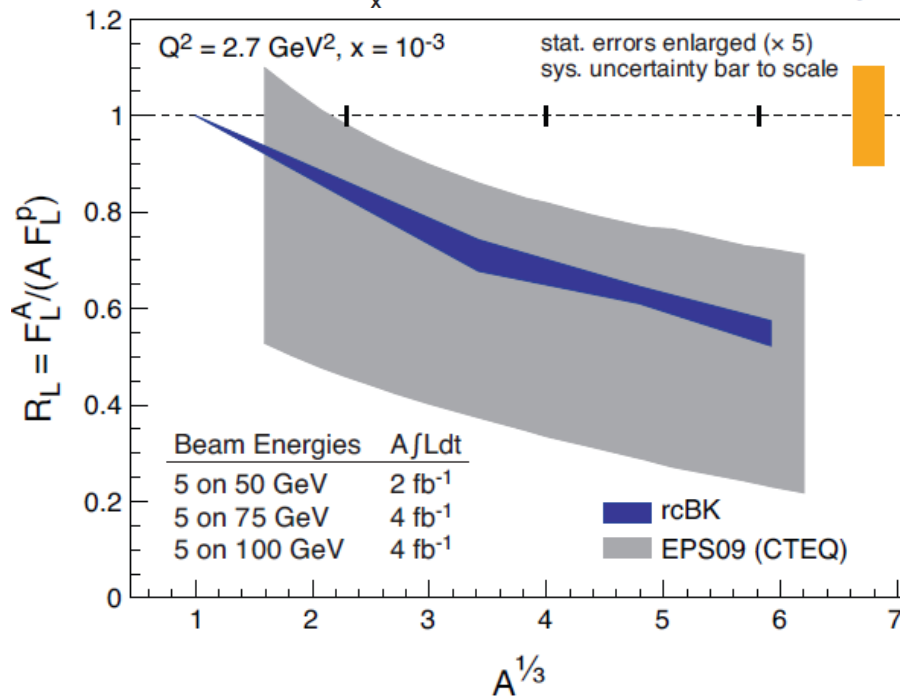
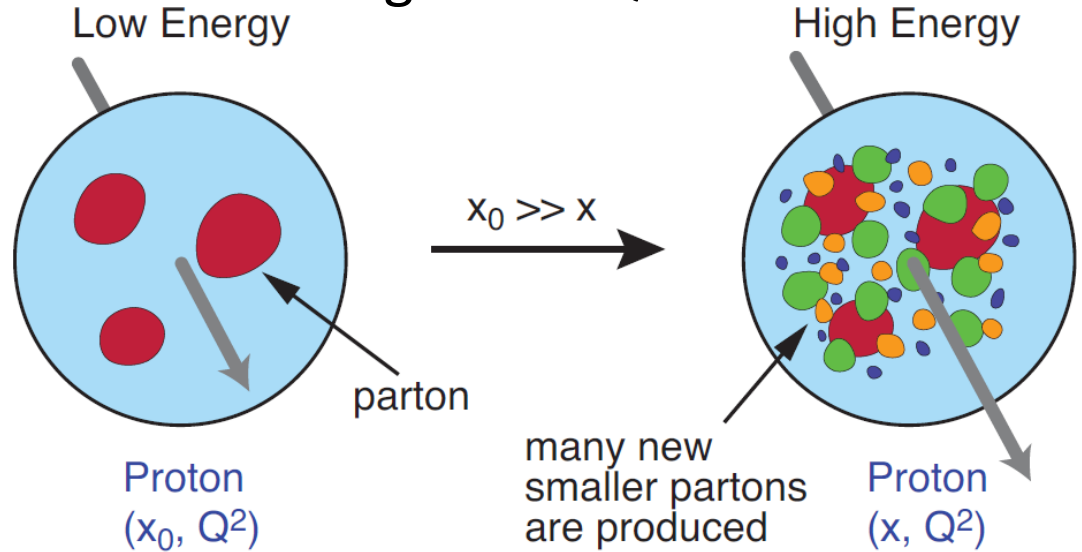
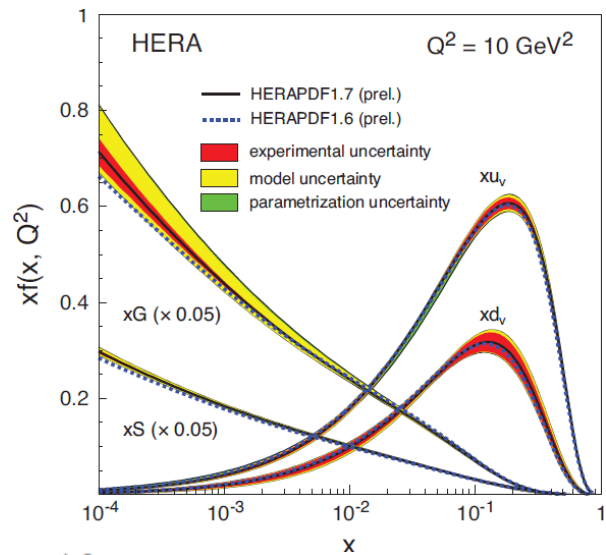
The Tomography of the Nucleon - Spatial Imaging of Gluons and Sea Quarks

Generalized parton distributions (GPDs) can be extracted from suitable **exclusive** scattering processes in e+p collisions – **deeply virtual Compton scattering (DVCS)** or vector meson production

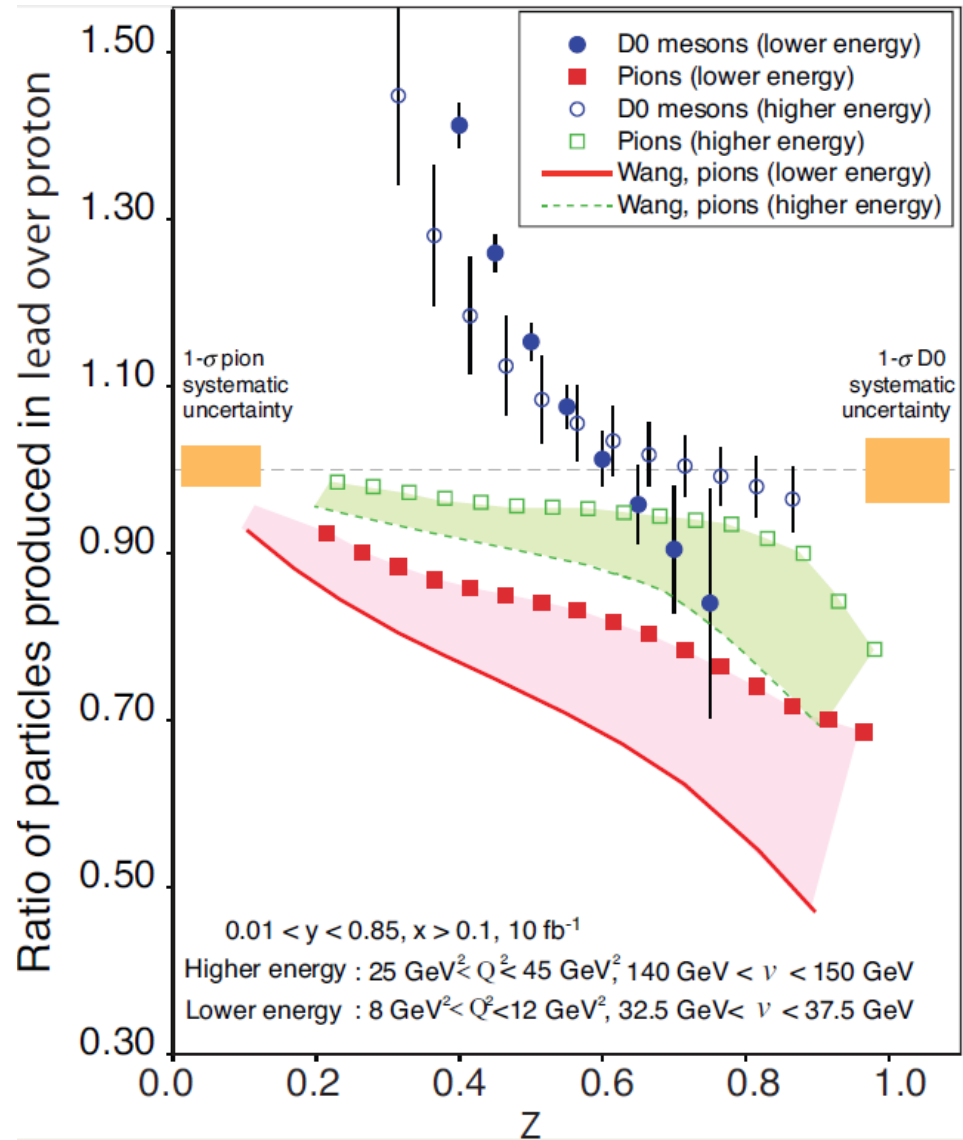
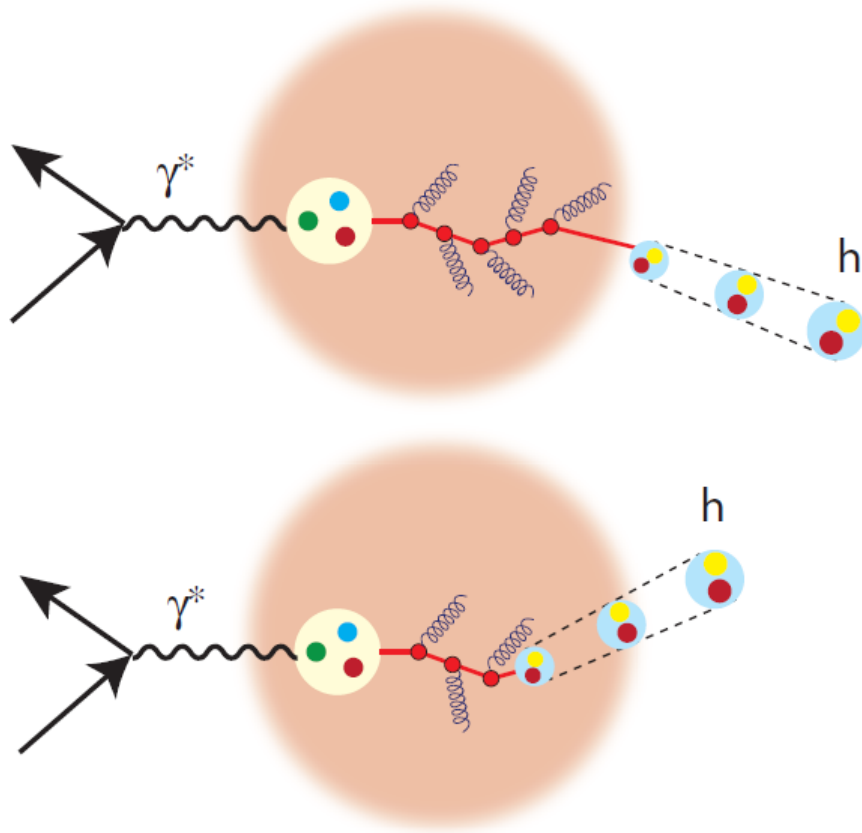
GPDs unify the concepts of parton densities and of elastic form factors, containing detailed information about spin-orbit correlations and the angular momentum carried by partons, including their spin and orbital motion.



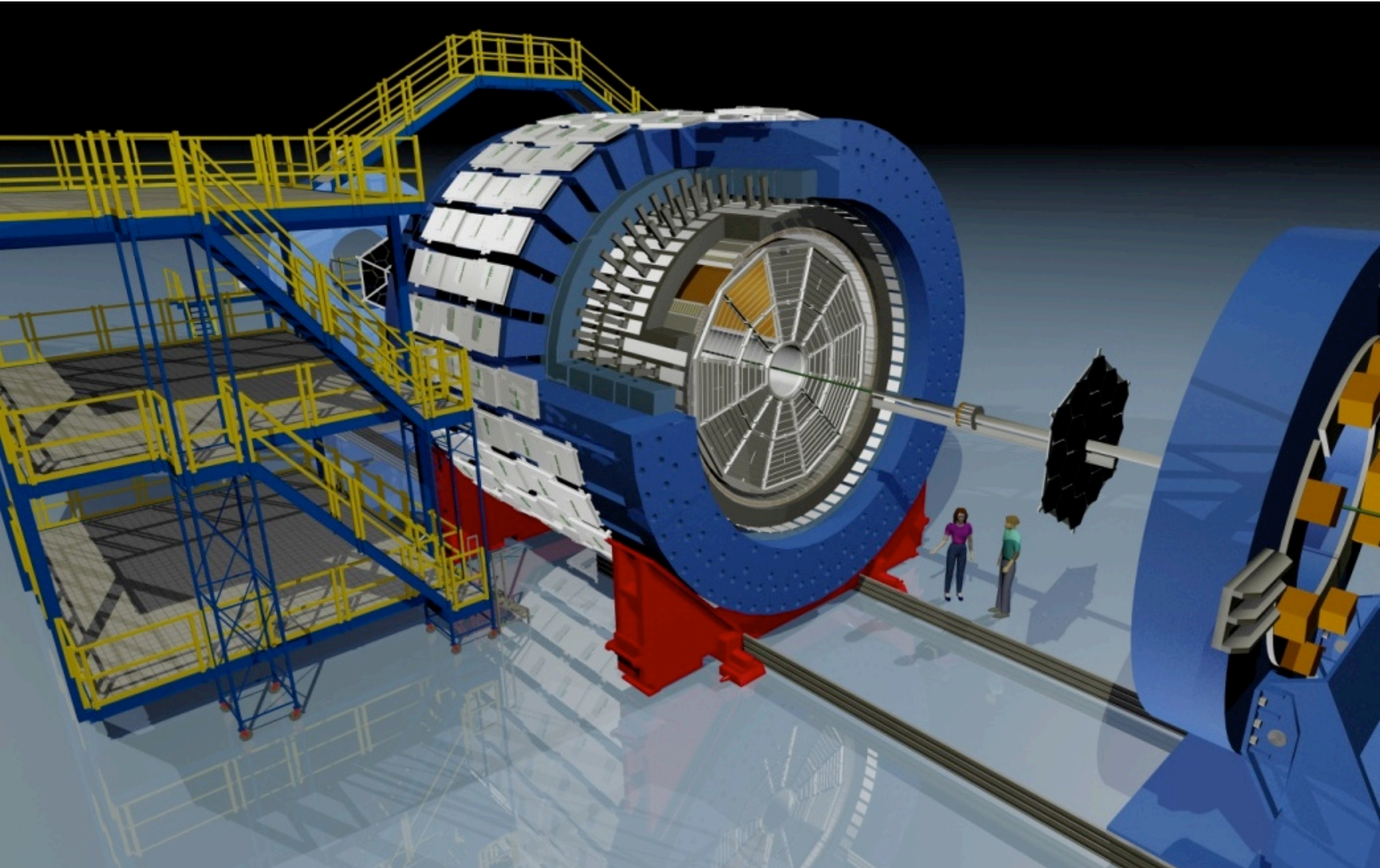
Gluon Saturation - a New Regime of QCD



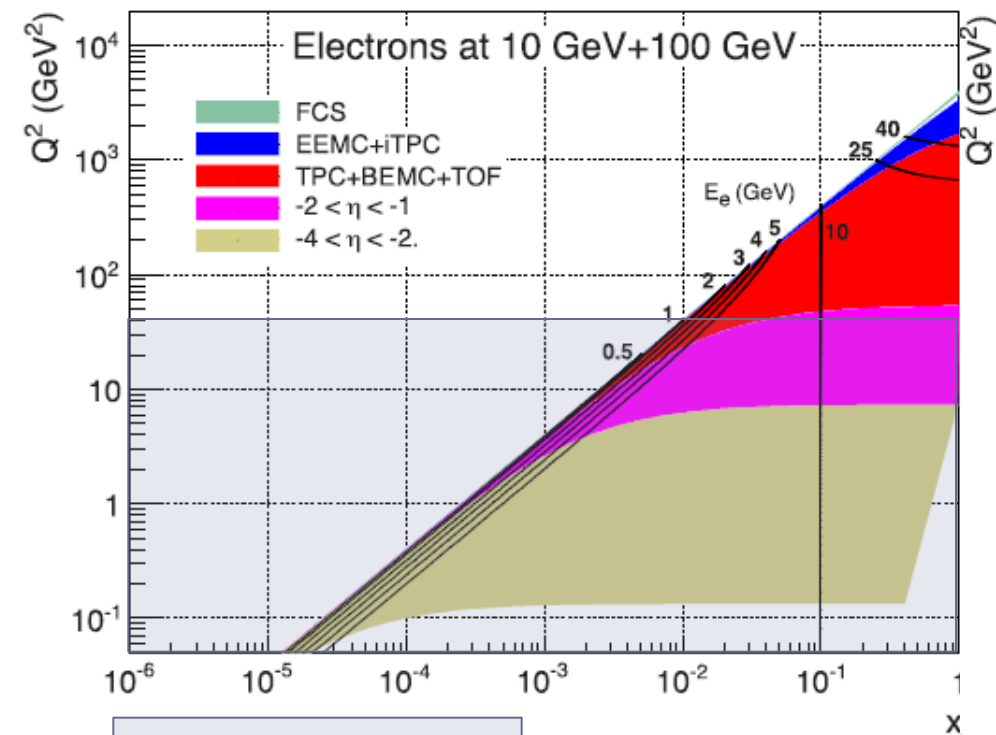
Propagation of a Color Charge in cold QCD Matter



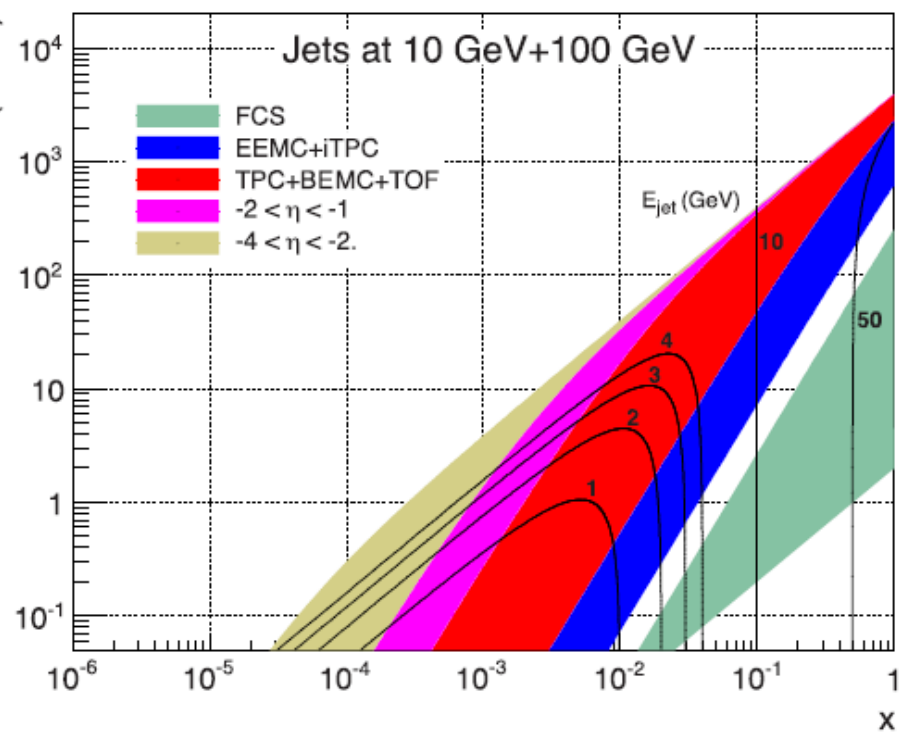
STAR experiment and eSTAR upgrade



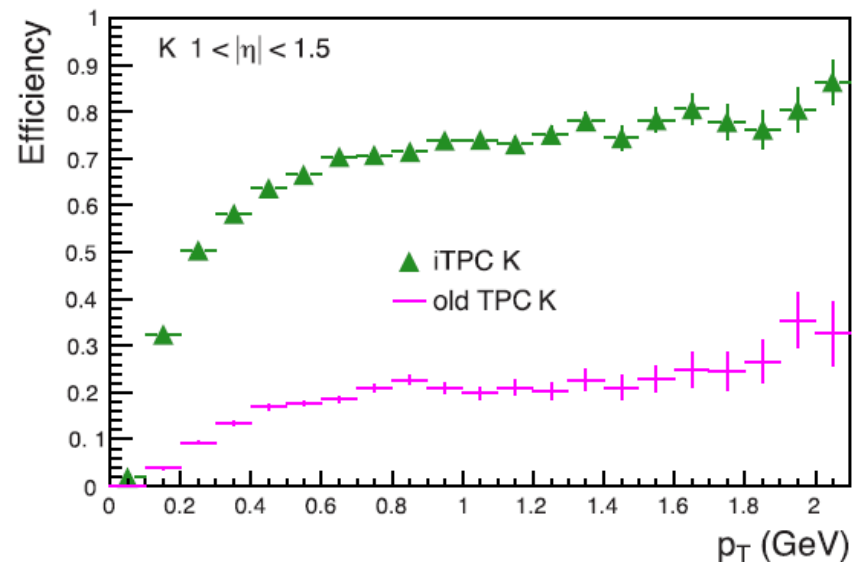
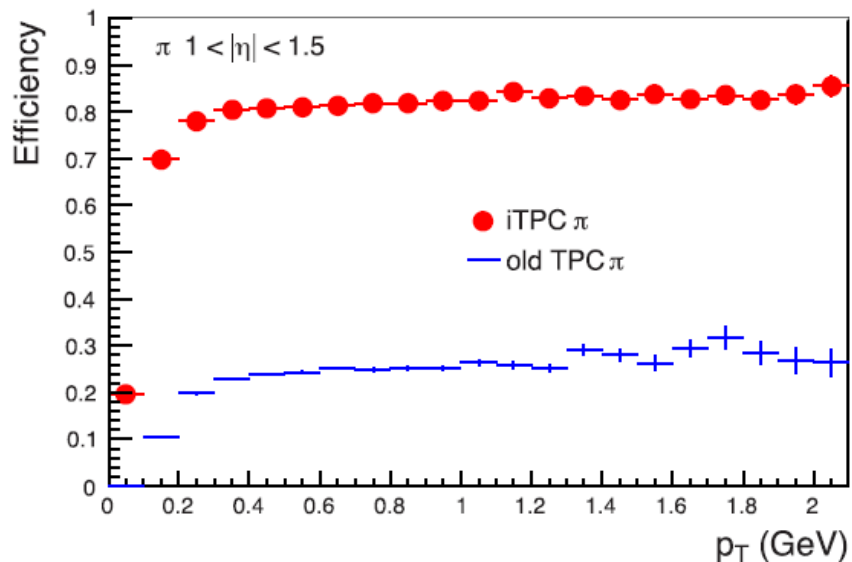
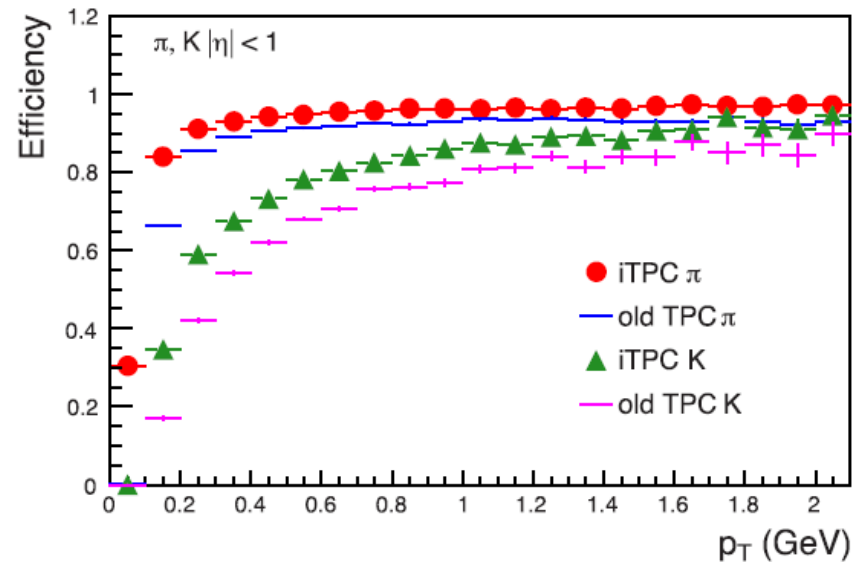
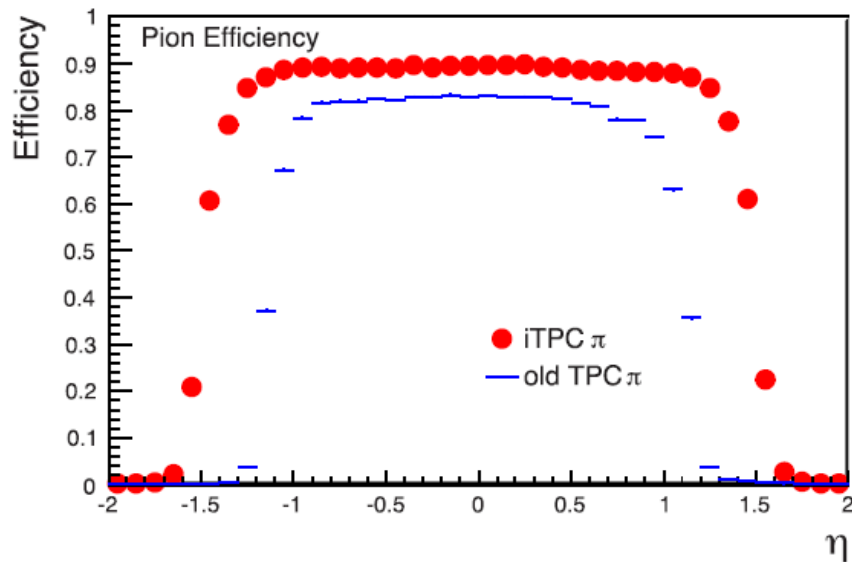
eSTAR kinematics coverage



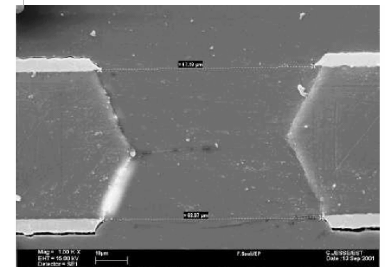
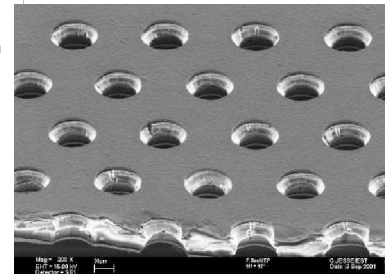
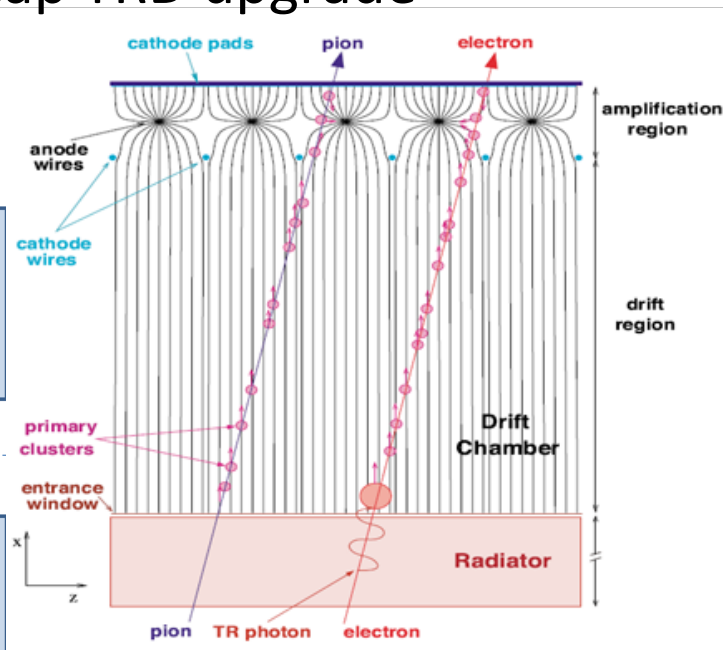
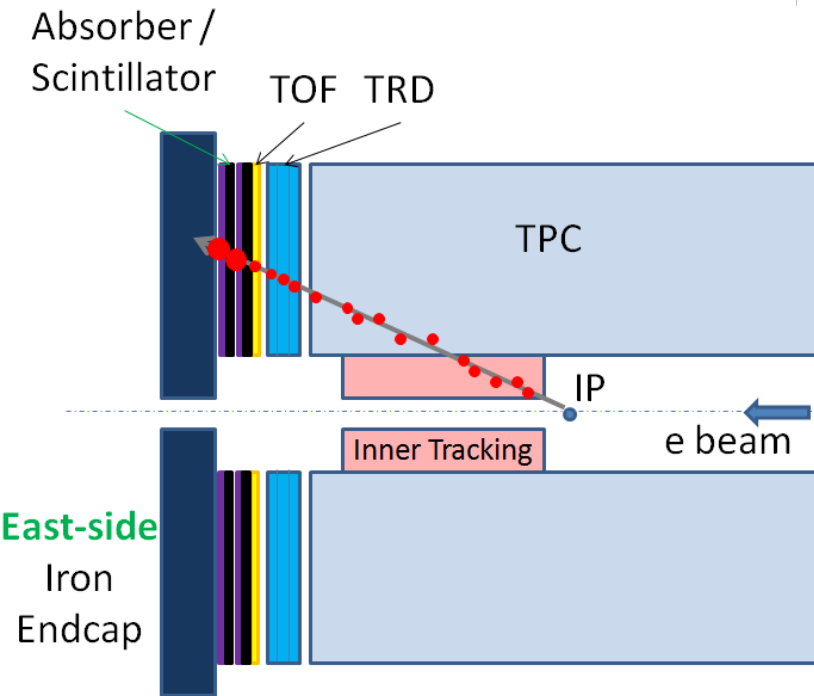
eSTAR upgrade



iTPC upgrade

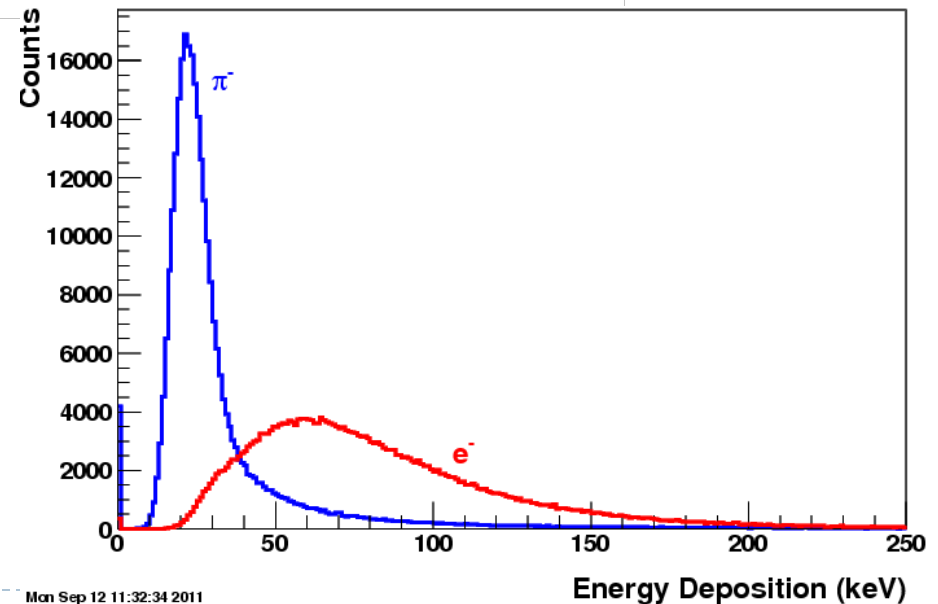


Endcap TRD upgrade



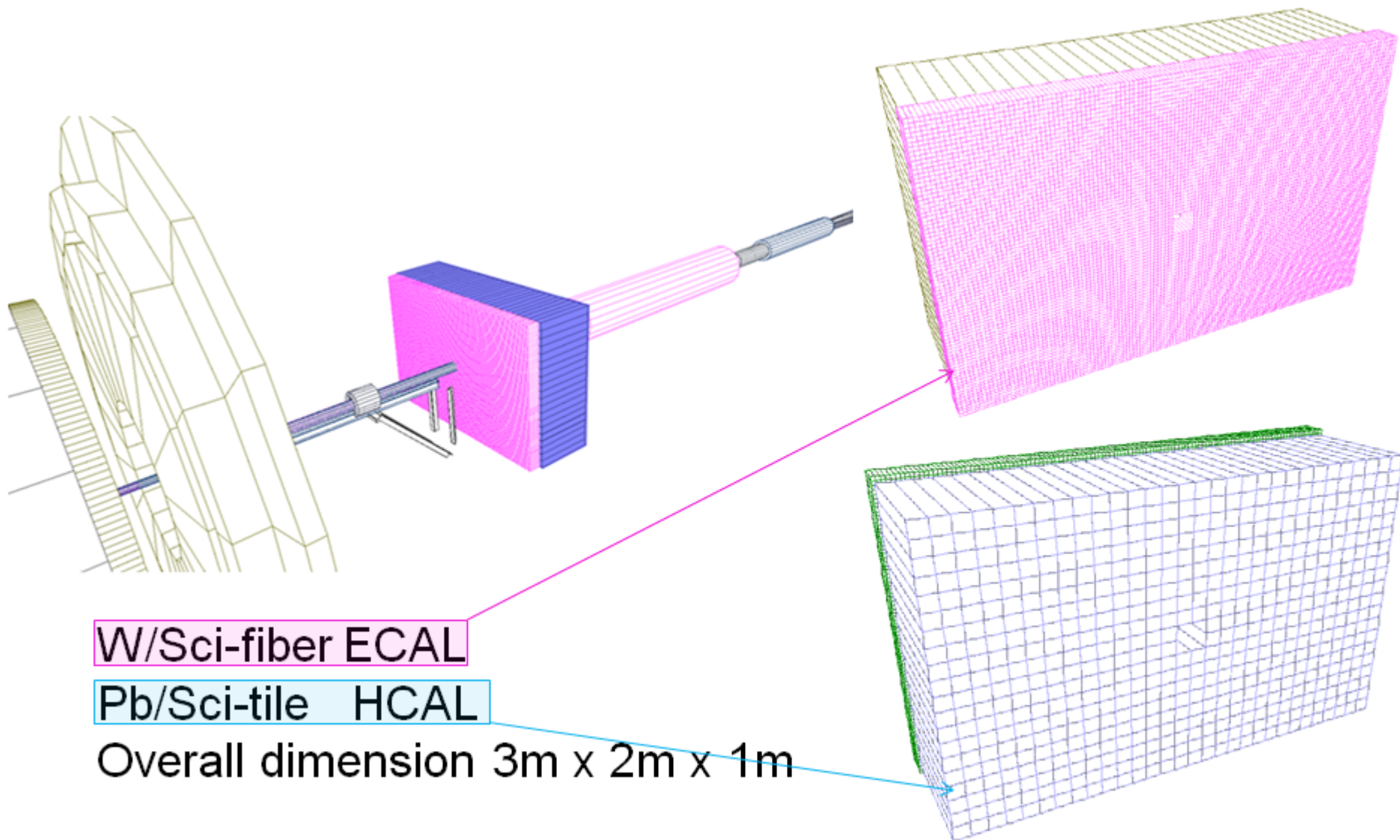
Recoil electron tagging in ep/eA collision

- Within <70cm space inside endcap
- TOF as start-time for BTOF and MTD
- TOF + dE/dx for electron ID
- TOF for hadron PID
- Extended tracking with precise points
- High-precision dE/dx (Xe+CO₂) TRD



Mon Sep 12 11:32:34 2011

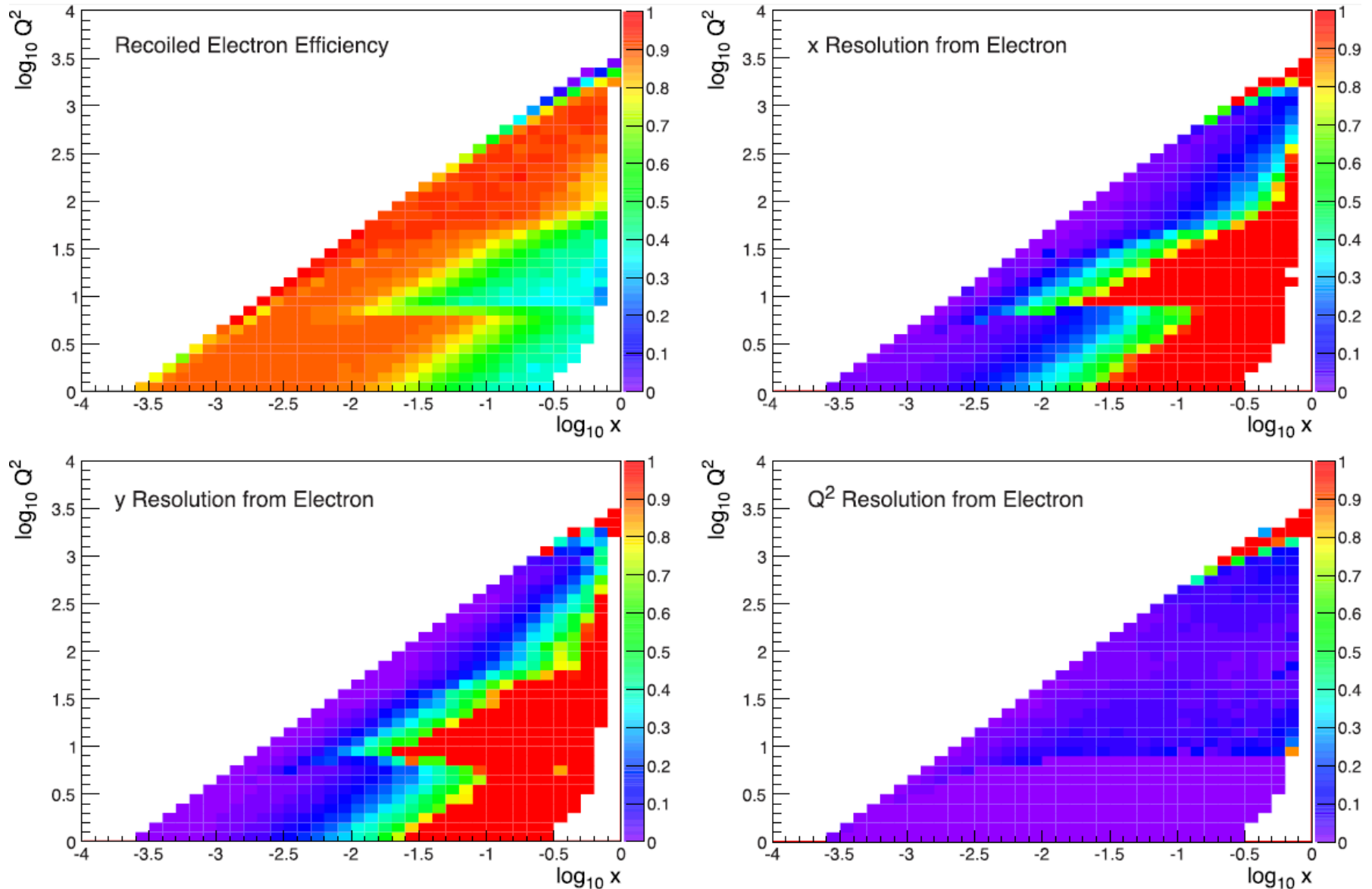
FCS upgrade



eSTAR expected performance

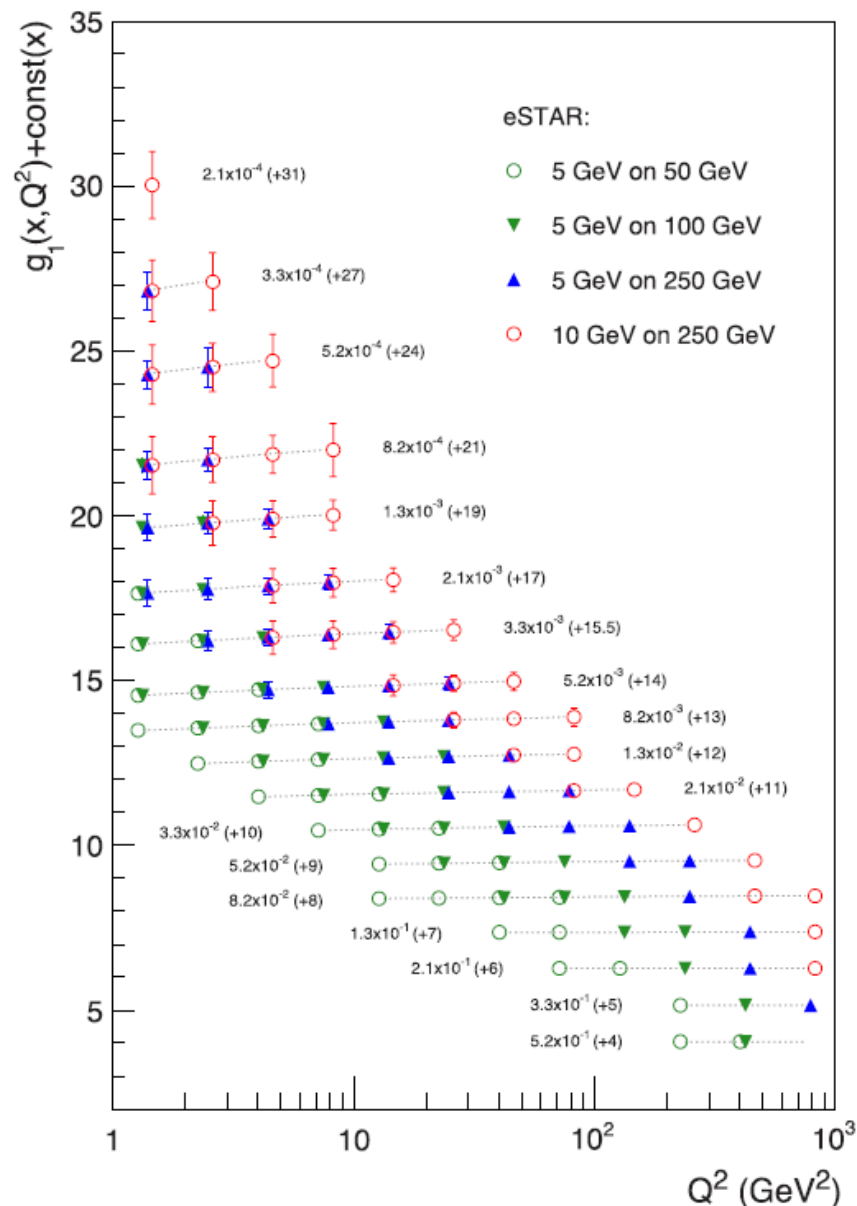
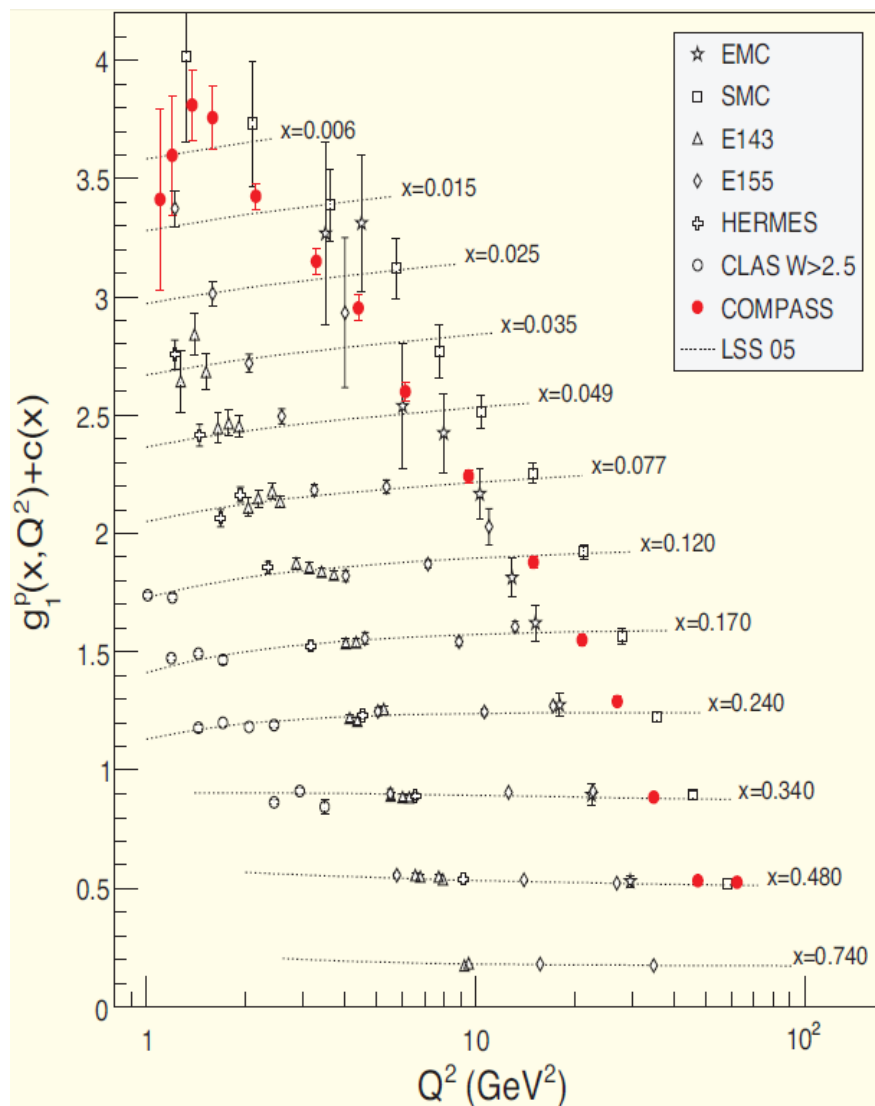
| | e^{\pm} | γ/π^0 | π^{\pm} | K^{\pm} | p |
|------------------|--|----------------|---------------------------------|---------------------------|---------------------------|
| $-4 < \eta < -2$ | Y | Y | N | N | N |
| $-2 < \eta < -1$ | Y | N | $0.1 < p < 15 \text{ GeV}$ | $0.1 < p < 3 \text{ GeV}$ | $0.1 < p < 5 \text{ GeV}$ |
| $-1 < \eta < 1$ | Y | Y | | | |
| $1 < \eta < 1.7$ | Y | Y | | | |
| $1.7 < \eta < 2$ | Y | Y | N | N | N |
| $2 < \eta < 2.5$ | Tracking without PID (charged hadrons) | | | | |
| $2.5 < \eta < 5$ | Y | Y | Tracking and Energy without PID | | |
| $-4 < \eta < 5$ | Hits | Hits | Hits | Hits | Hits |

DIS kinematics with eSTAR



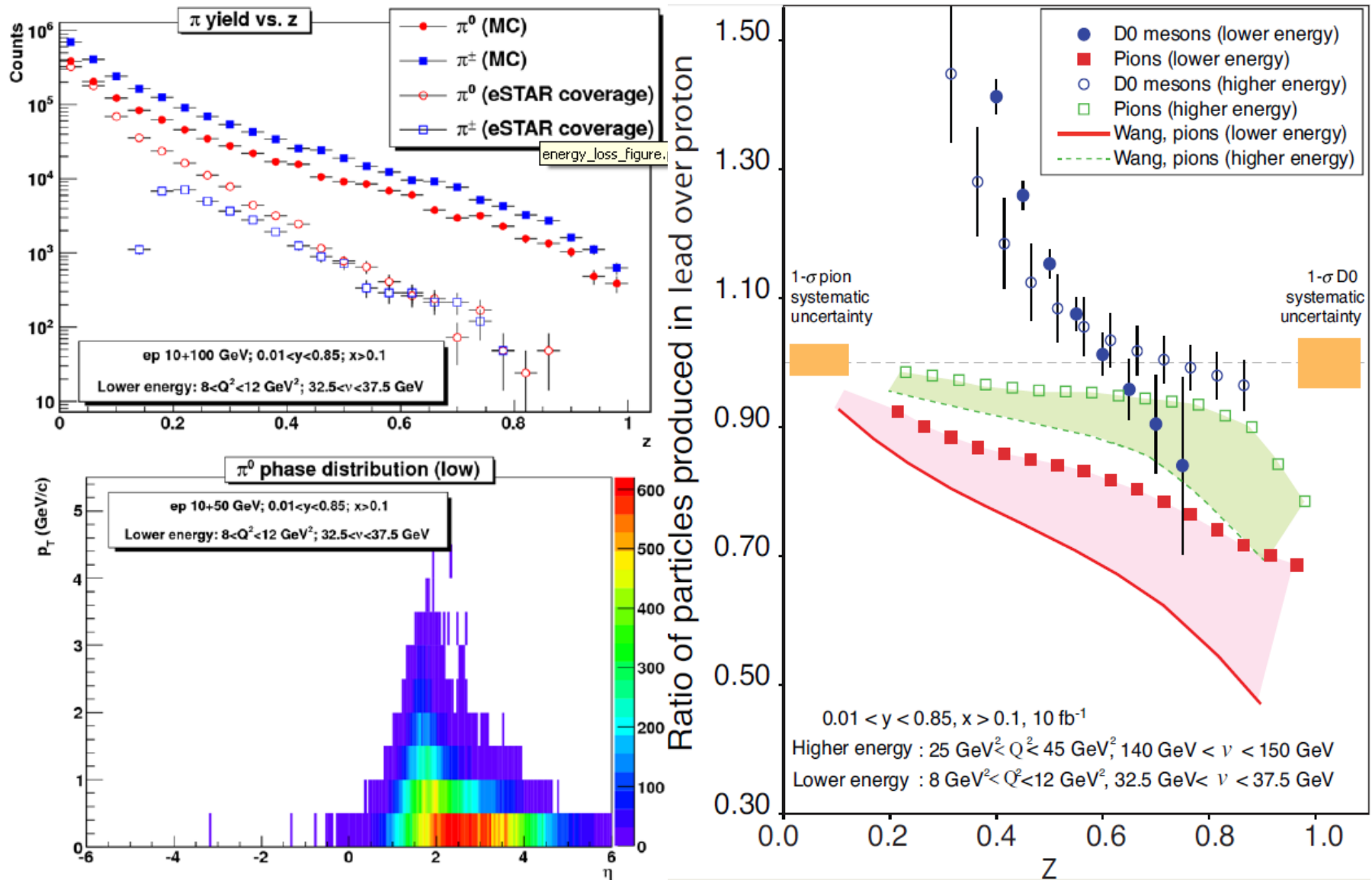
eSTAR observable and deliverable science - I

quark and gluon helicity parton distribution



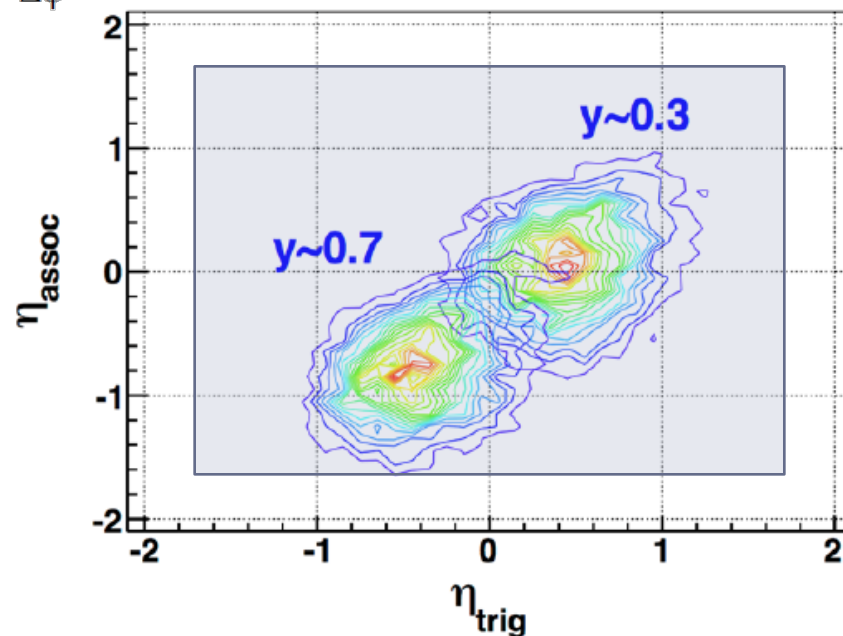
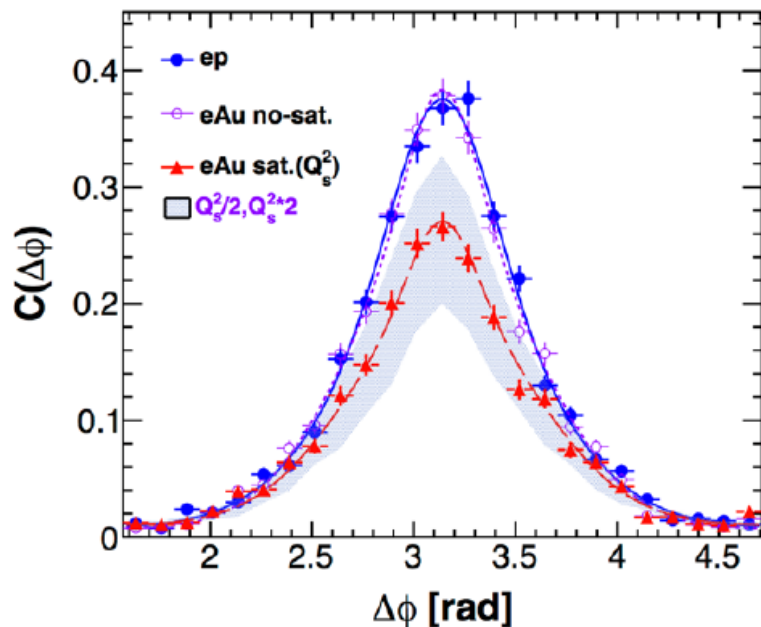
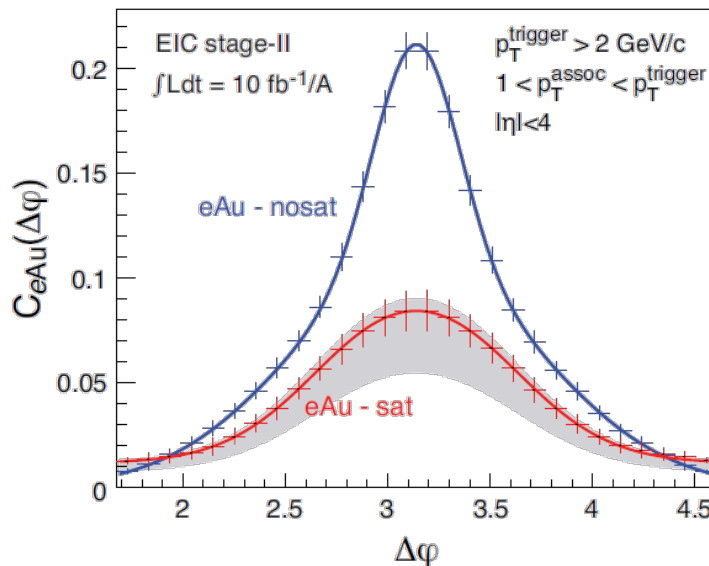
eSTAR observable and deliverable science - II

Propagation of a color charge in cold QCD Matter



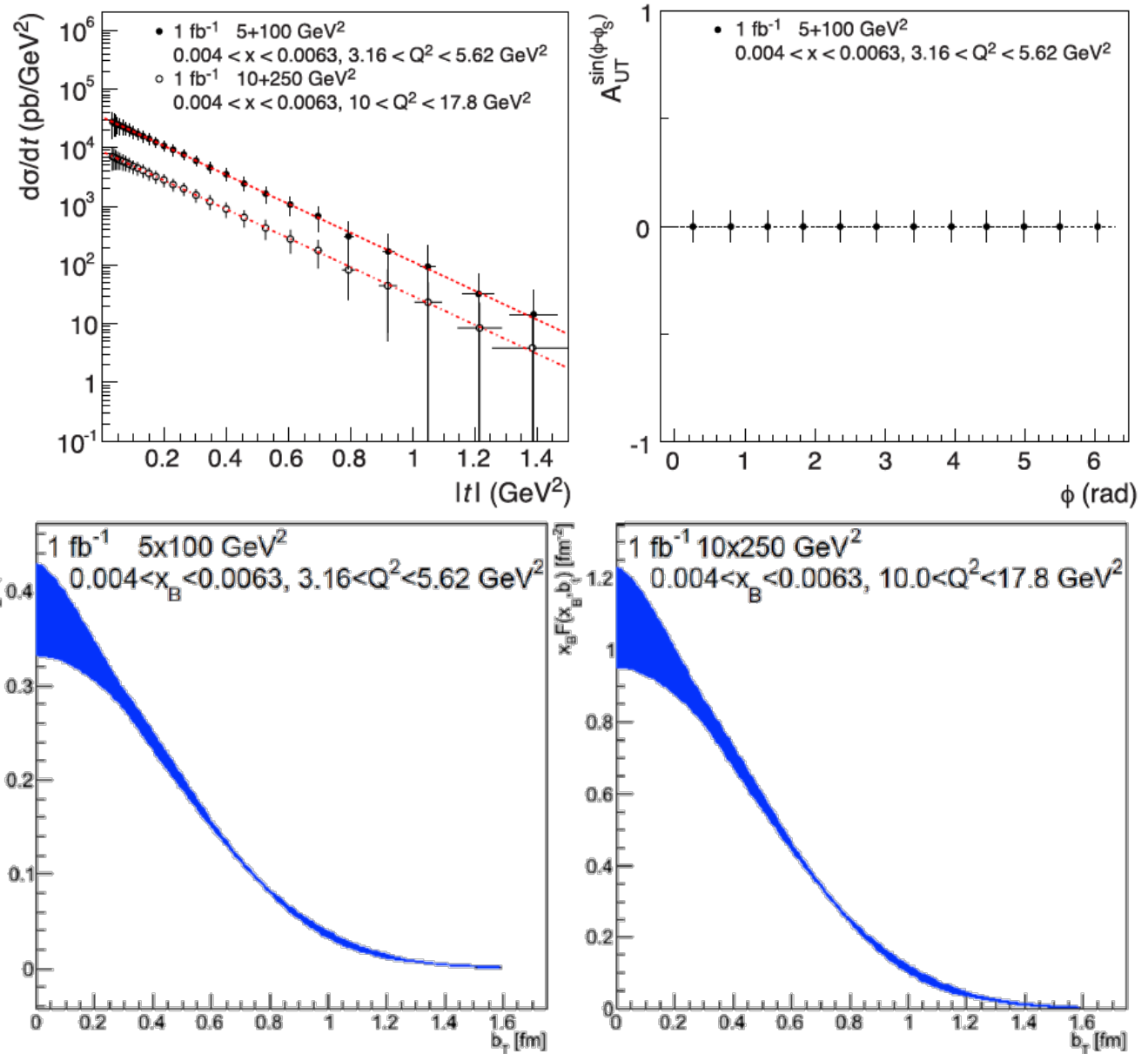
eSTAR observable and deliverable science - III

Di-hadron
correlation, probe
gluon saturation
effect in eA



eSTAR observable and deliverable science - IV

Use **DVCS** (or diffractive) measurement to extract the spatial distribution of partons



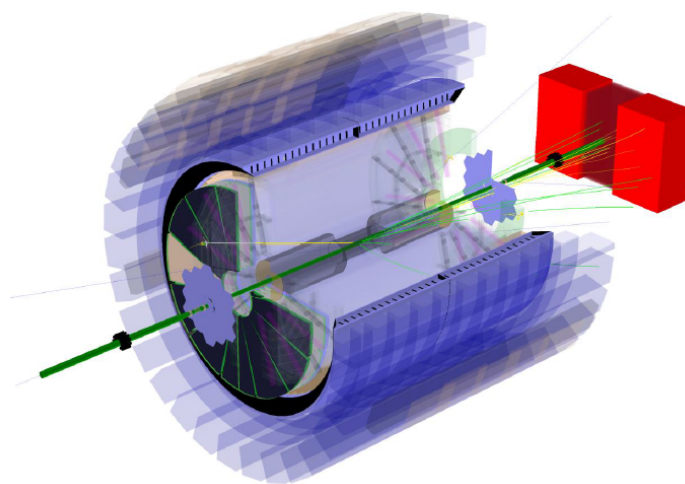


Electron Ion Collider: The Next QCD Frontier

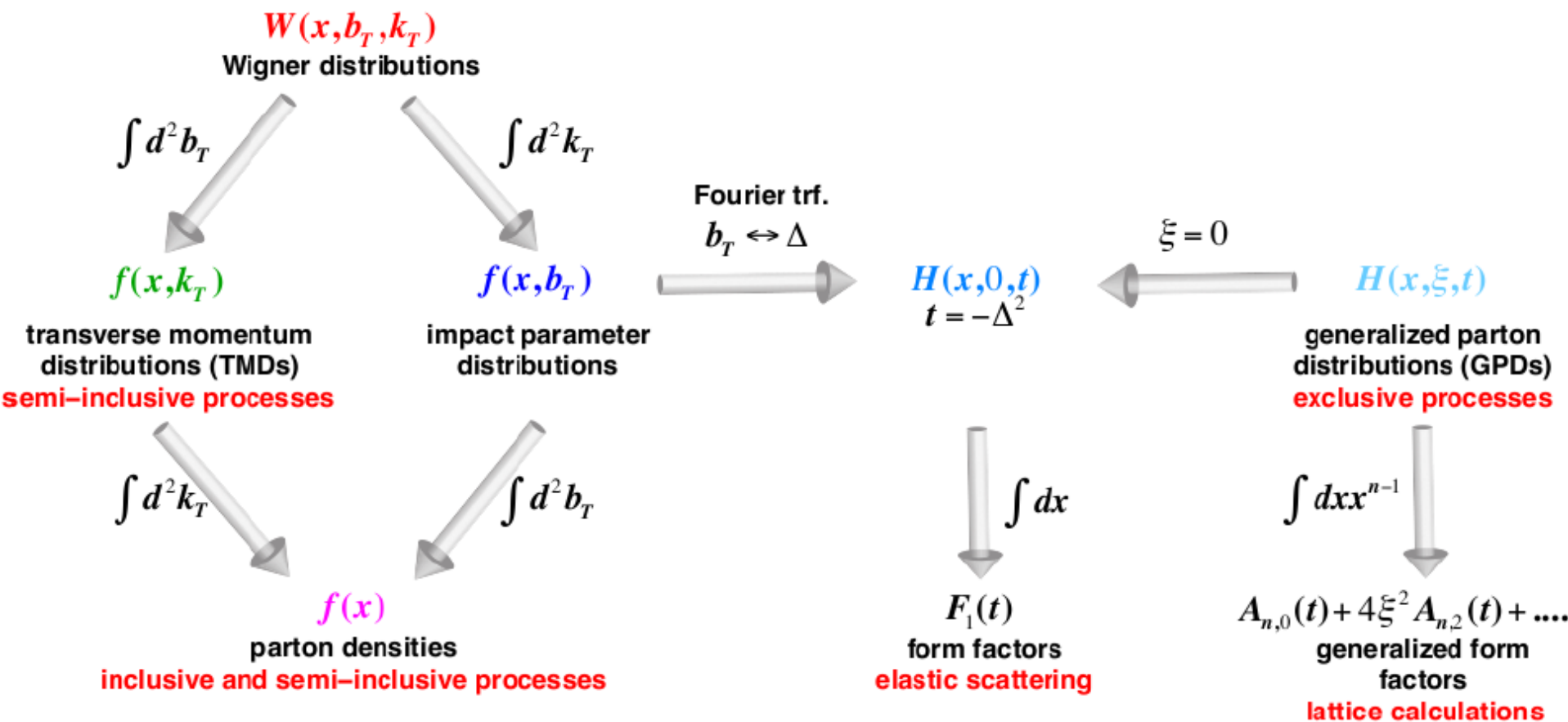
Understanding the glue
that binds us all

eSTAR: A Letter of Intent

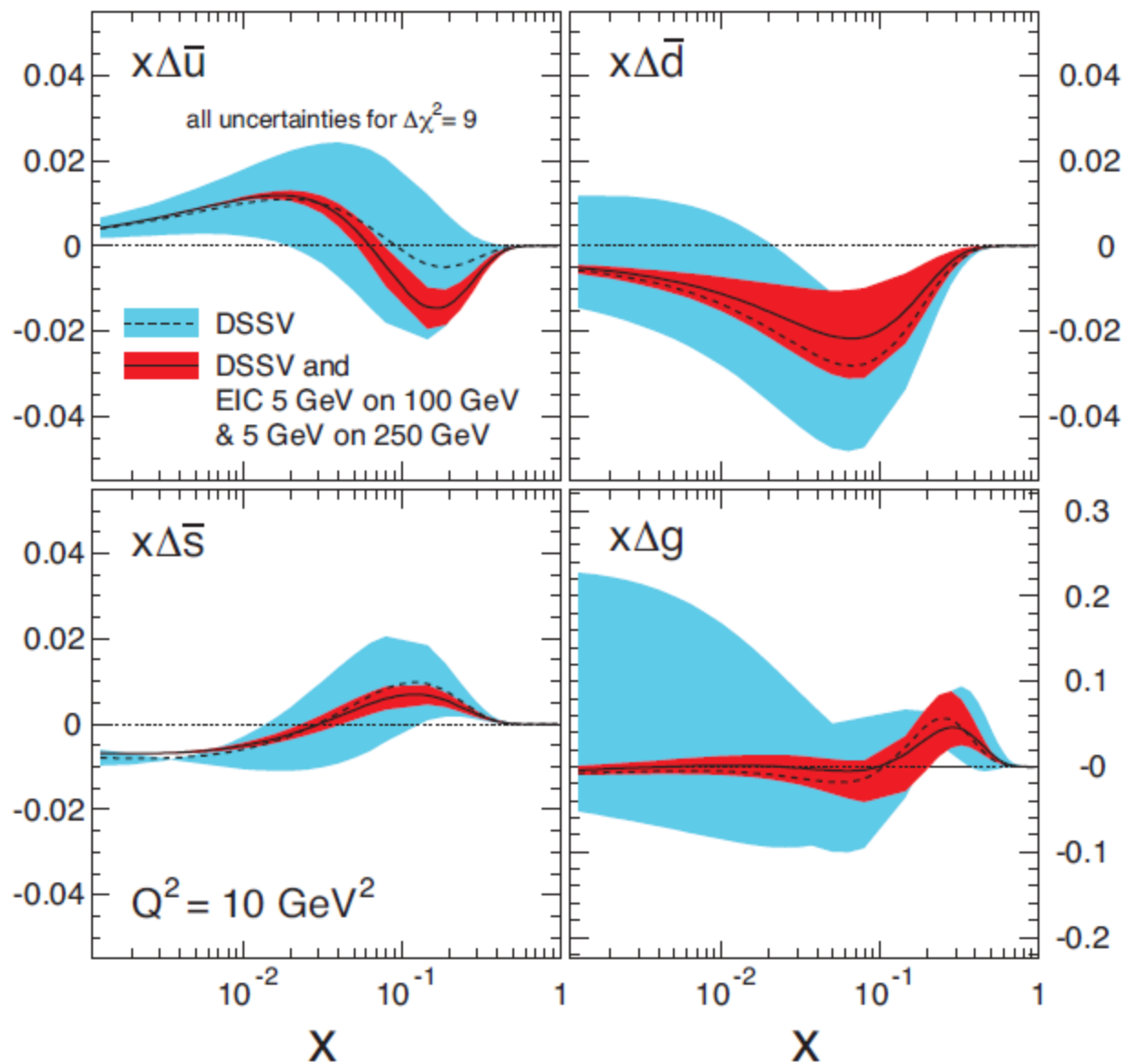
The STAR Collaboration



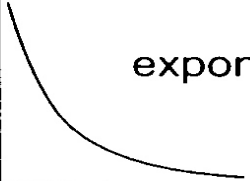
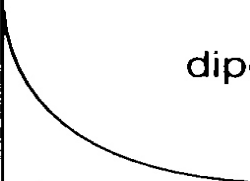
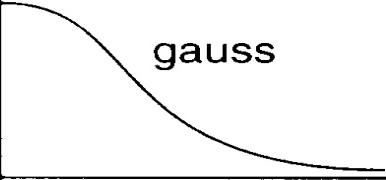
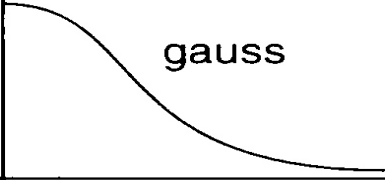

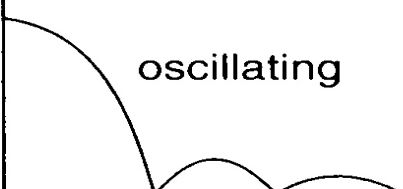
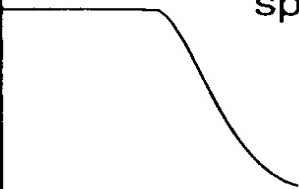
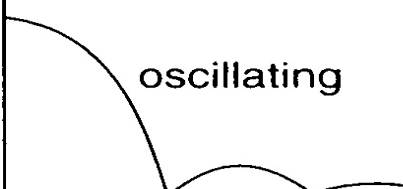
Backup slides

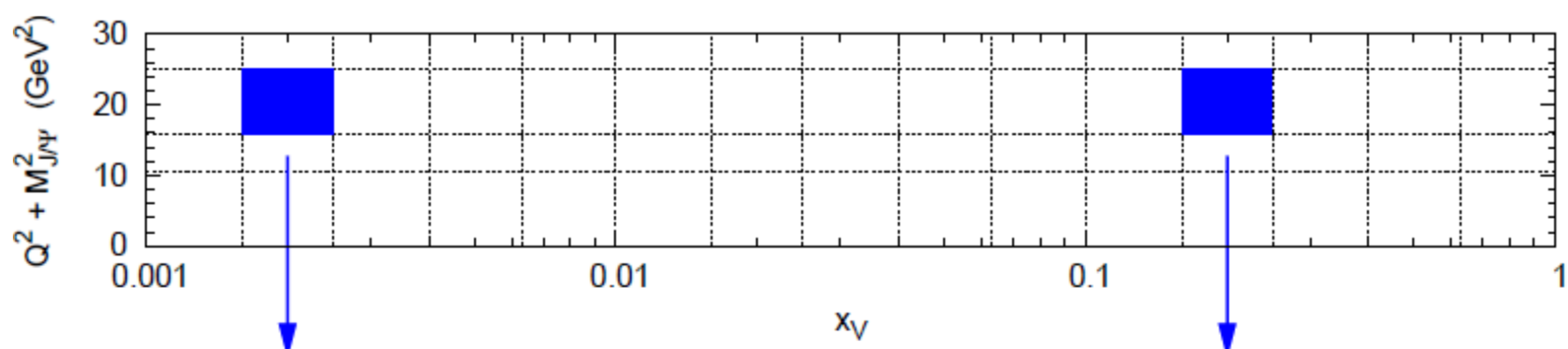


1. Proton spin: Within just a few months of operation, the EIC would be able to deliver decisive measurements, which no other facility in the world could achieve, on how much the intrinsic spin of quarks and gluons contribute to the proton spin as shown in Fig. 1.2 (Right).
2. The motion of quarks and gluons in the proton: Semi-inclusive measurements with polarized beams would enable us to selectively probe with precision the correlation between the spin of a fast moving proton and the correlated transverse motion of both quarks and gluons within. Images in momentum space as shown in Fig. 1.3 are simply unattainable without the polarized electron and proton beams of the proposed EIC.
3. The tomographic images of the proton: By measuring exclusive processes, the EIC, with its unprecedented luminosity and detector coverage, would create detailed images of the proton gluonic matter distribution, as shown in Fig. 1.4, as well as images of sea quarks. Such measurements would reveal aspects of proton structure that are intimately connected with QCD dynamics at large distances.
4. QCD matter at an extreme gluon density: By measuring the diffractive cross-sections together with the total DIS cross-sections in electron+proton and electron+nucleus collisions as shown in Fig. 1.6, the EIC would provide the first unambiguous evidence for the novel QCD matter of saturated gluons. The EIC is poised to explore with precision the new field of the collective dynamics of saturated gluons at high energies.
5. Quark hadronization: By measuring pion and D0 meson production in both electron+proton and electron+nucleus collisions, the EIC would provide the first measurement of the quark mass dependence of the hadronization along with the response of nuclear matter to a fast moving quark.



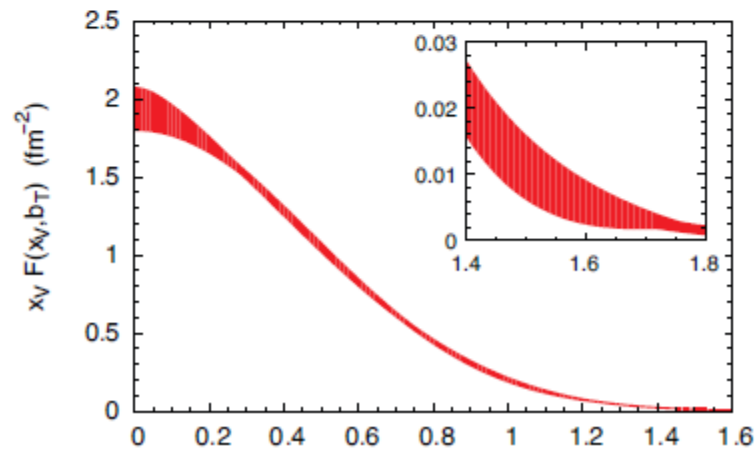
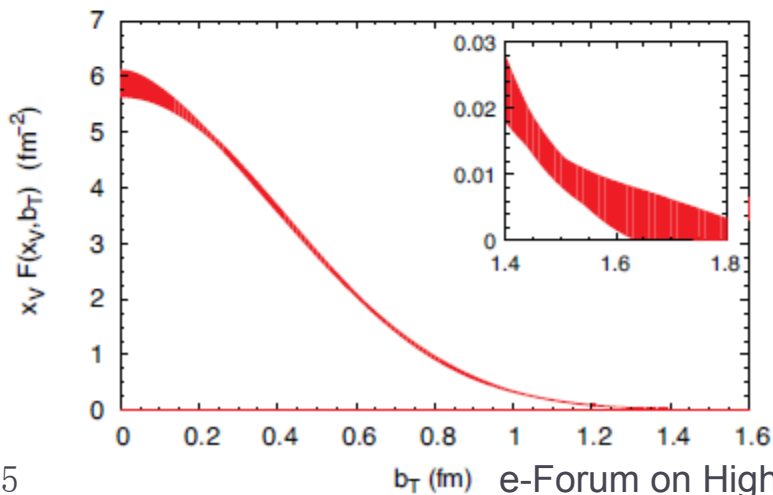
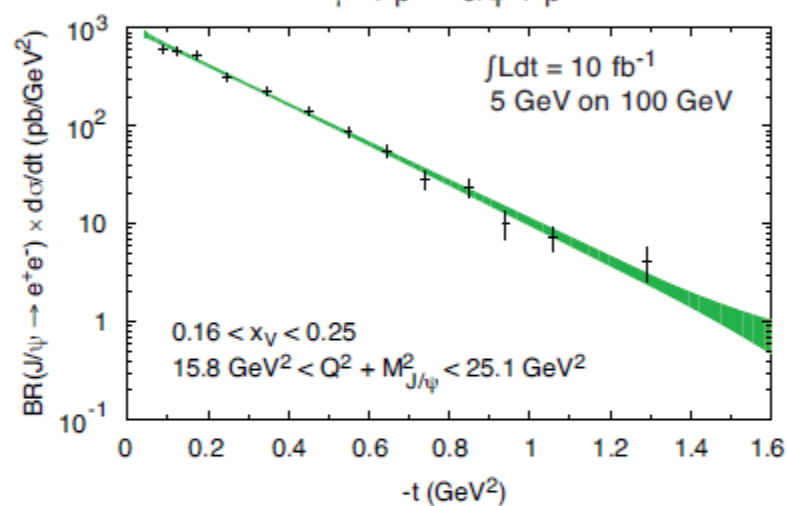
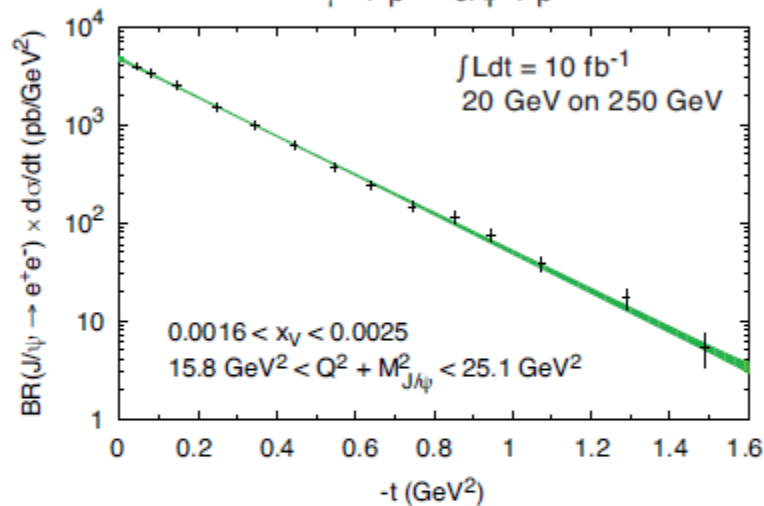
Form Factors

| $\rho(r)$ | $ F(q^2) $ | Example |
|---|--|--------------------|
| pointlike | constant | Electron |
|  exponential |  dipole | Proton |
|  gauss |  gauss | ${}^6\text{Li}$ |
|  homogeneous sphere |  oscillating | — |
|  sphere with a diffuse surface |  oscillating | ${}^{40}\text{Ca}$ |

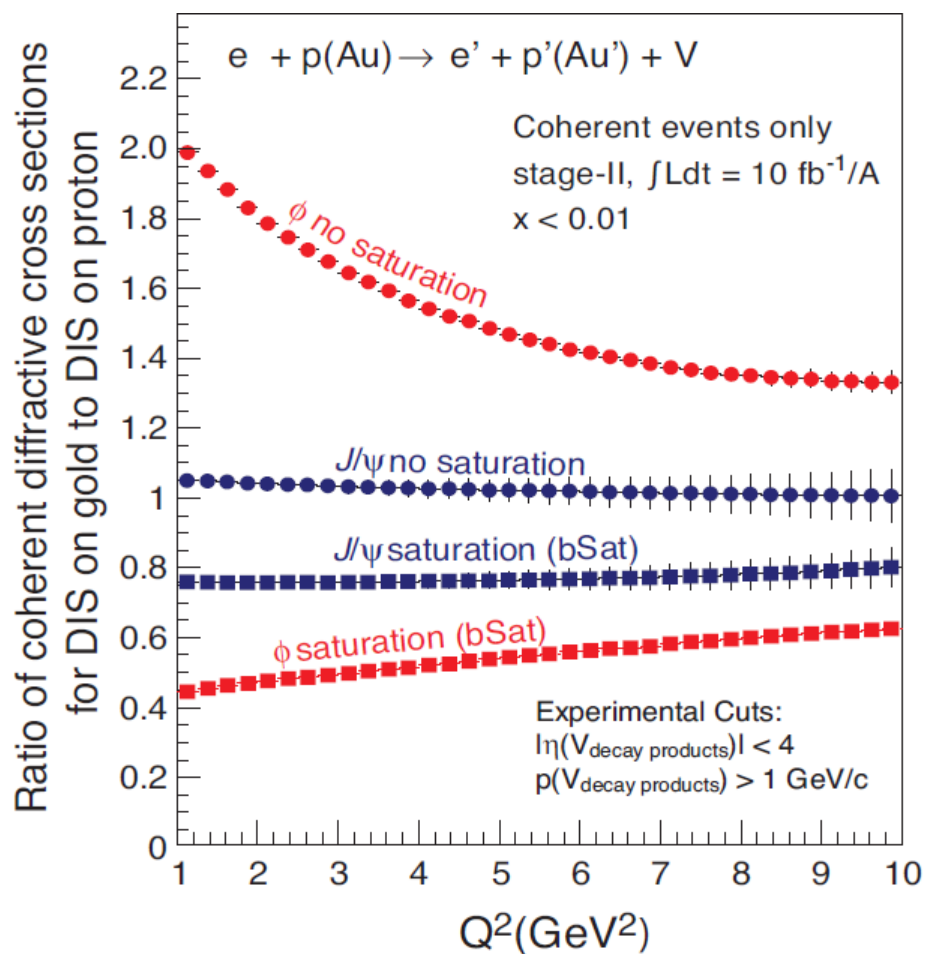
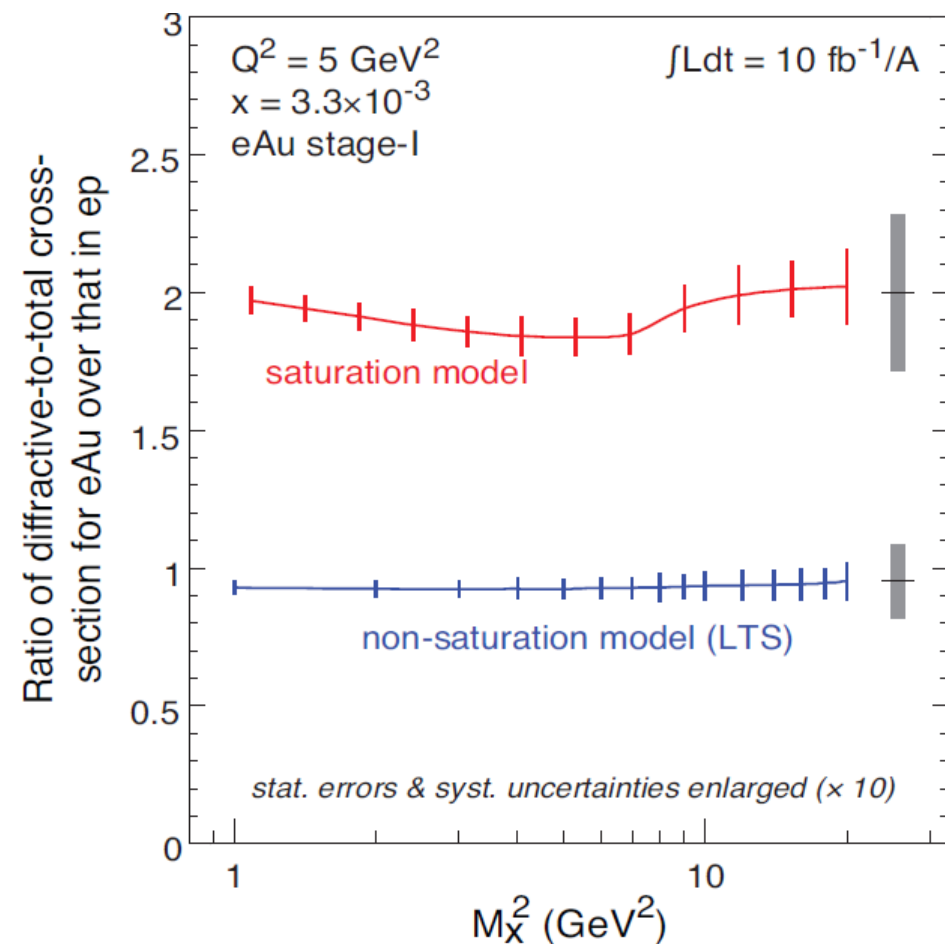


$\gamma^* + p \rightarrow J/\psi + p$

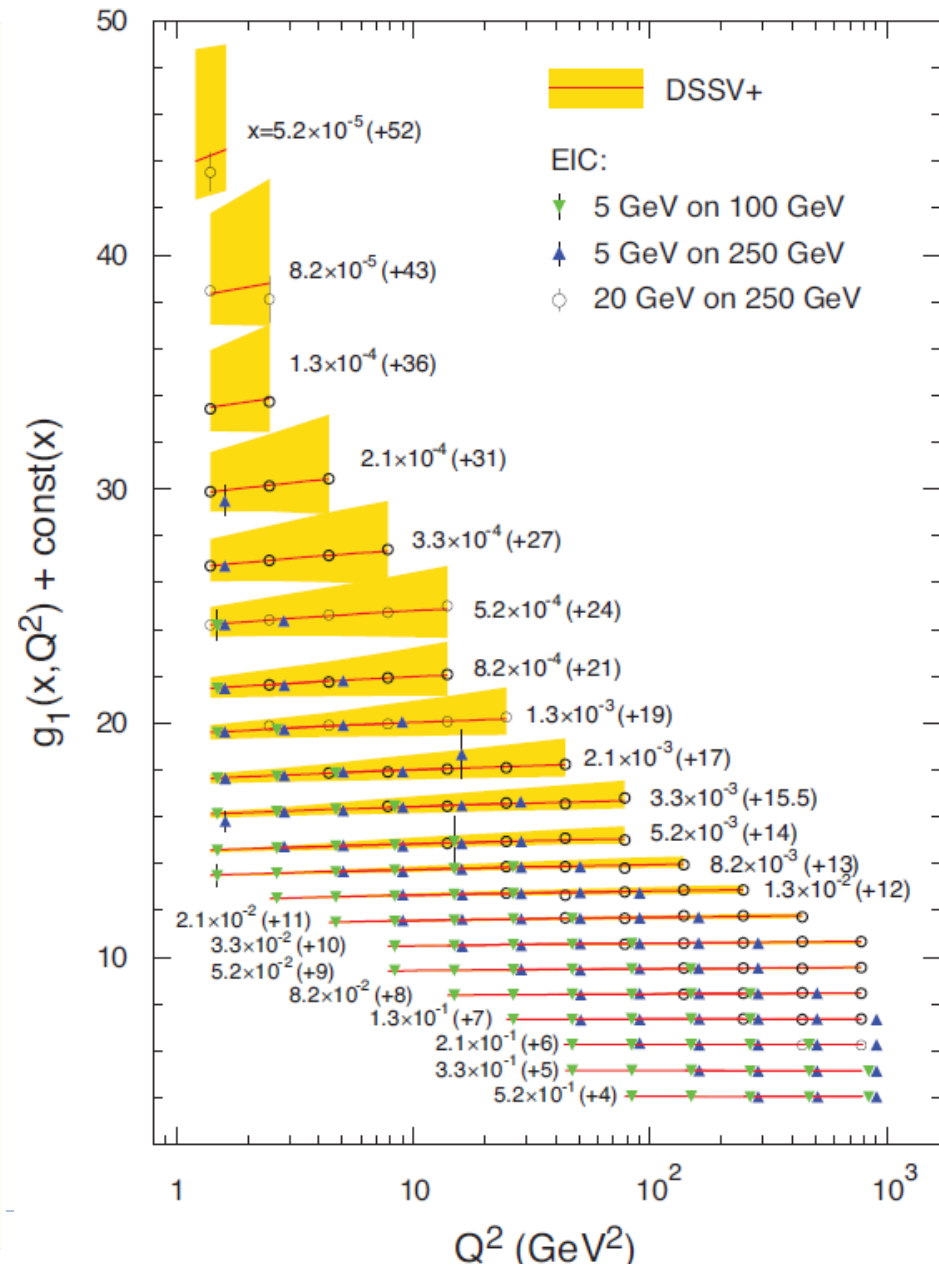
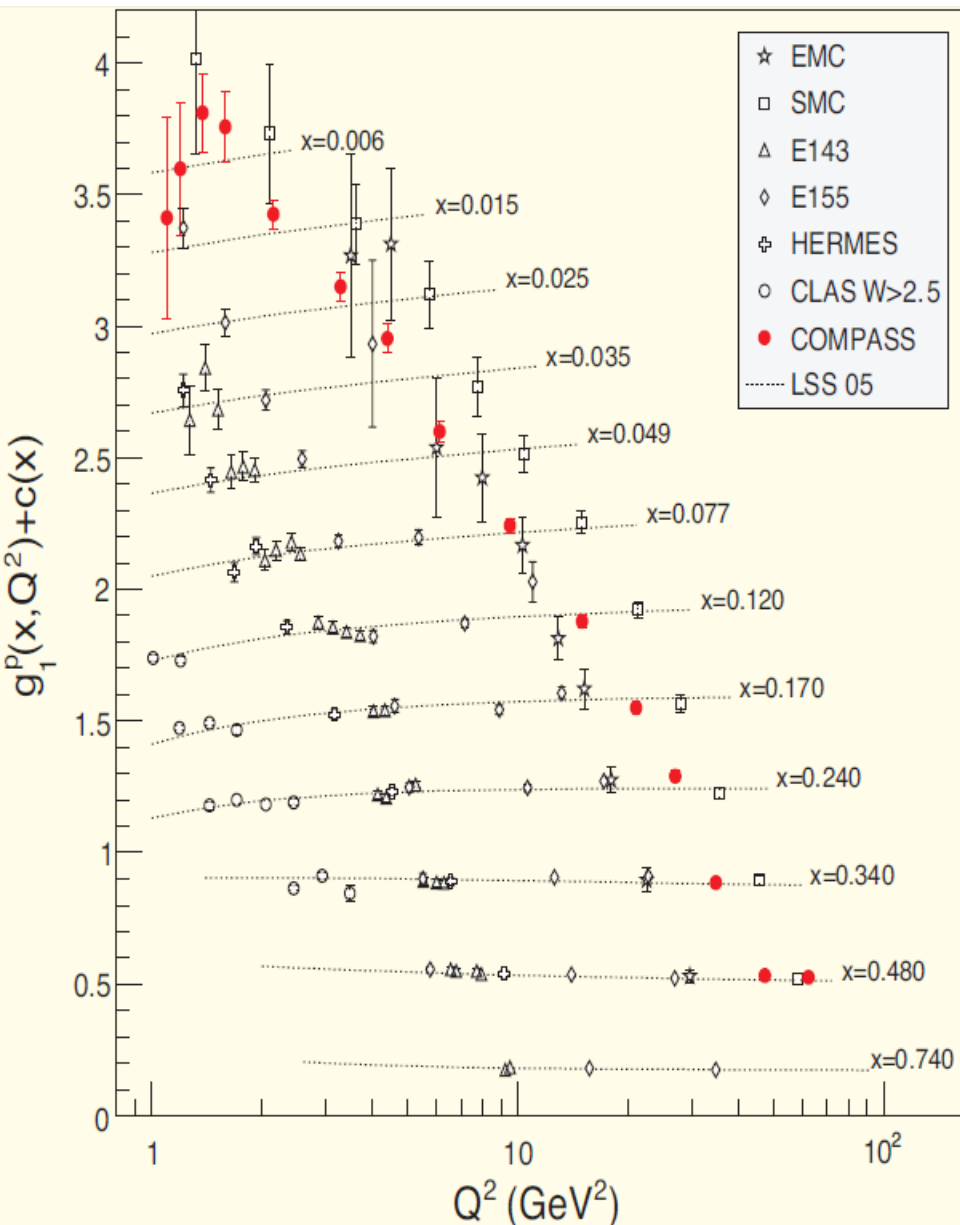
$\gamma^* + p \rightarrow J/\psi + p$



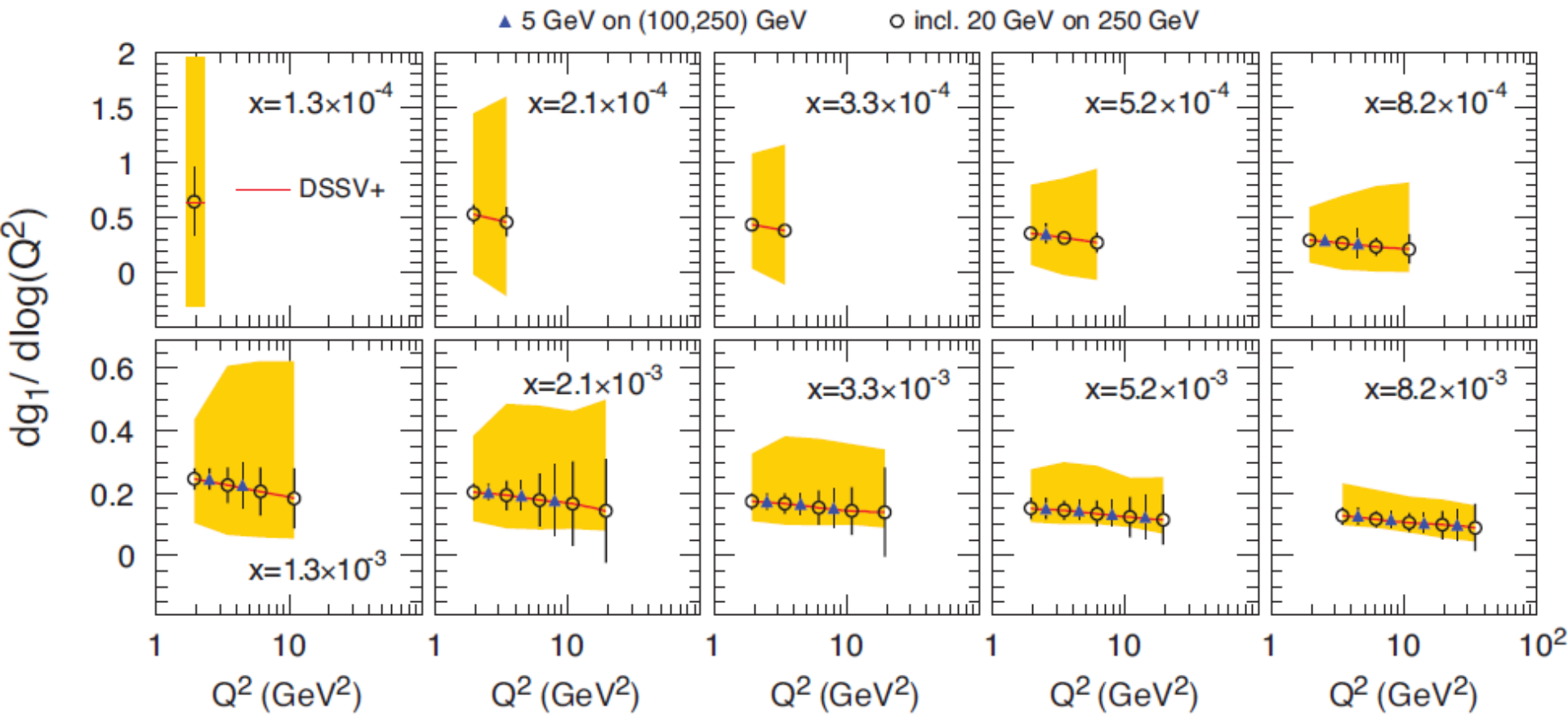
QCD at Extreme Parton Densities

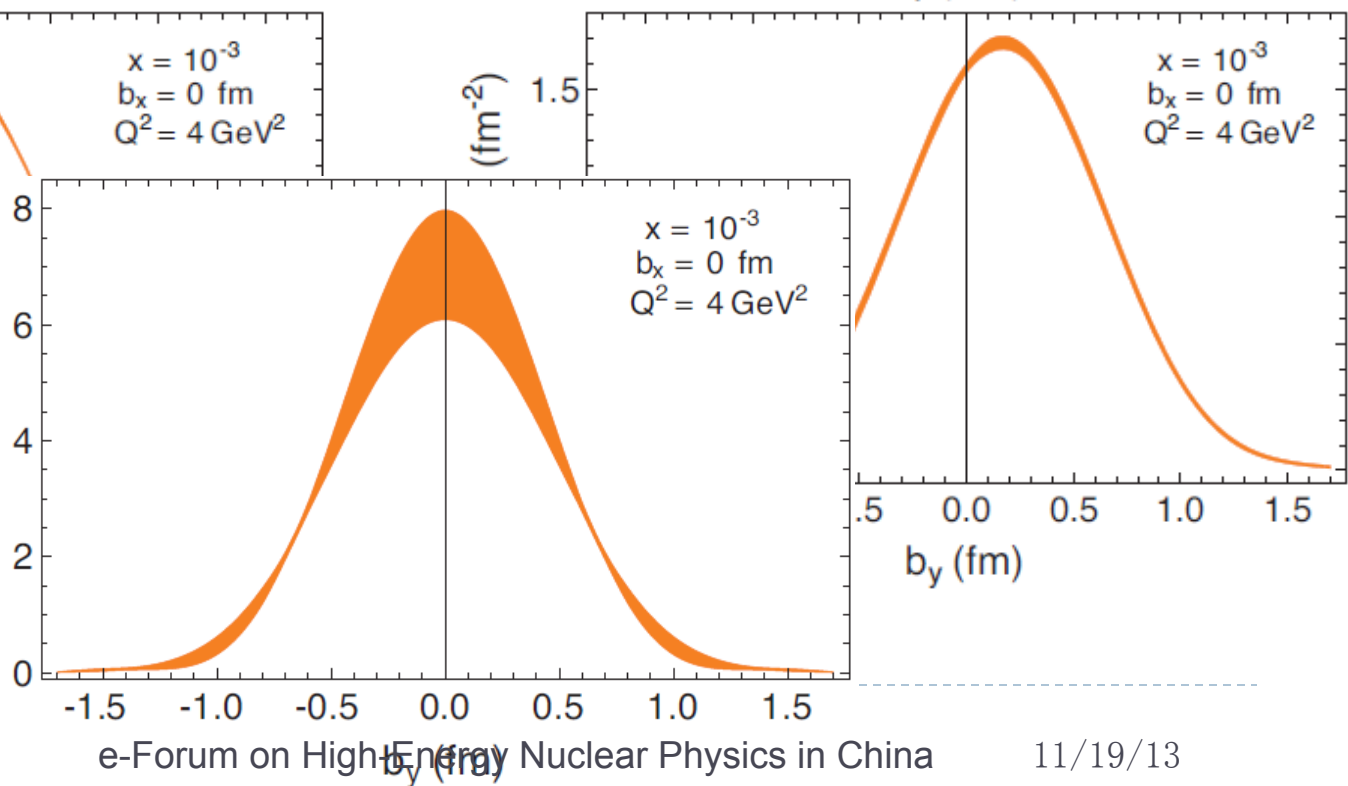
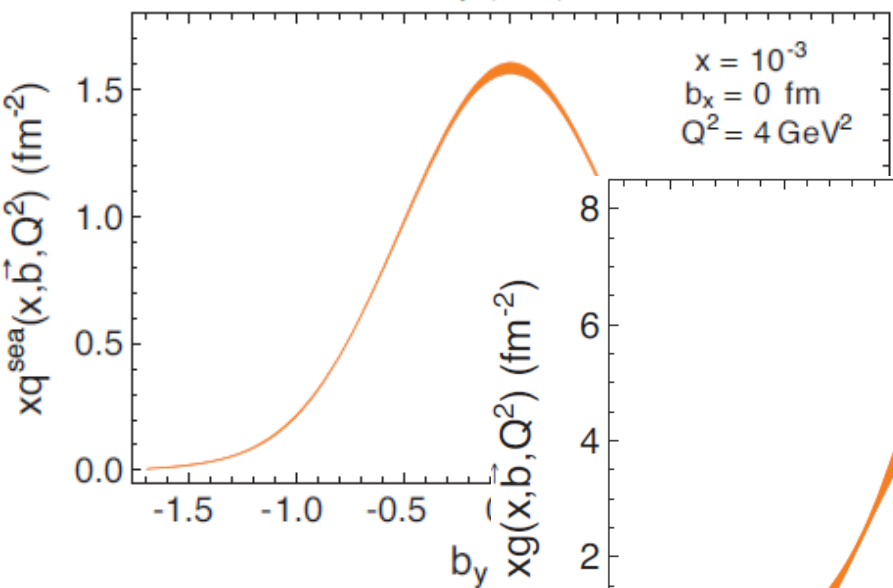
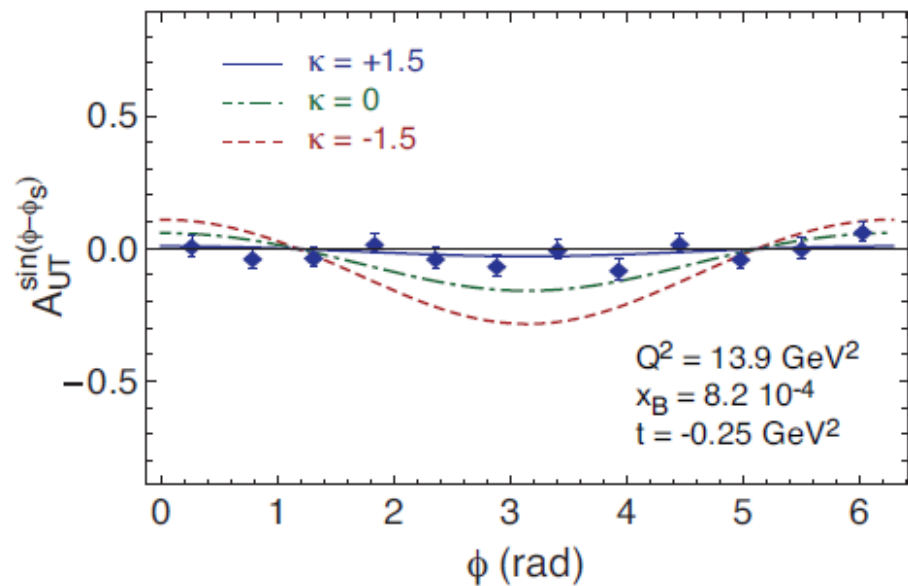
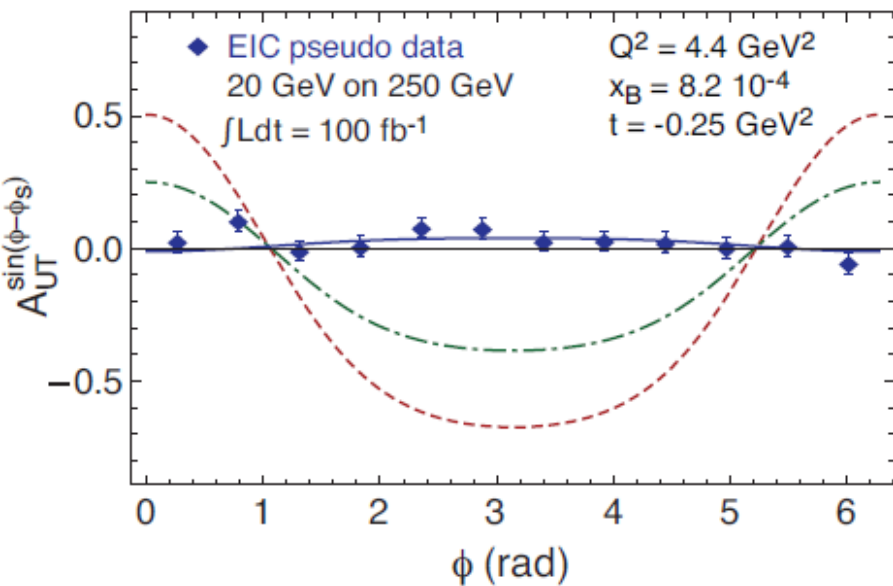


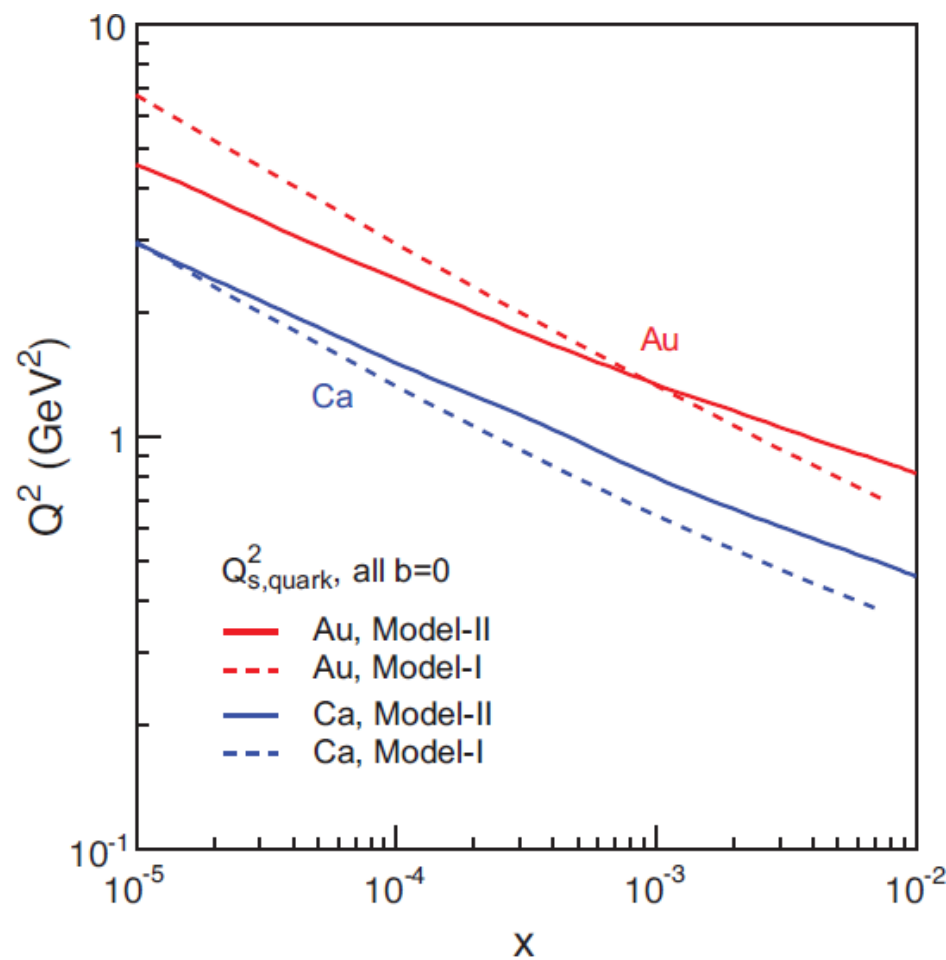
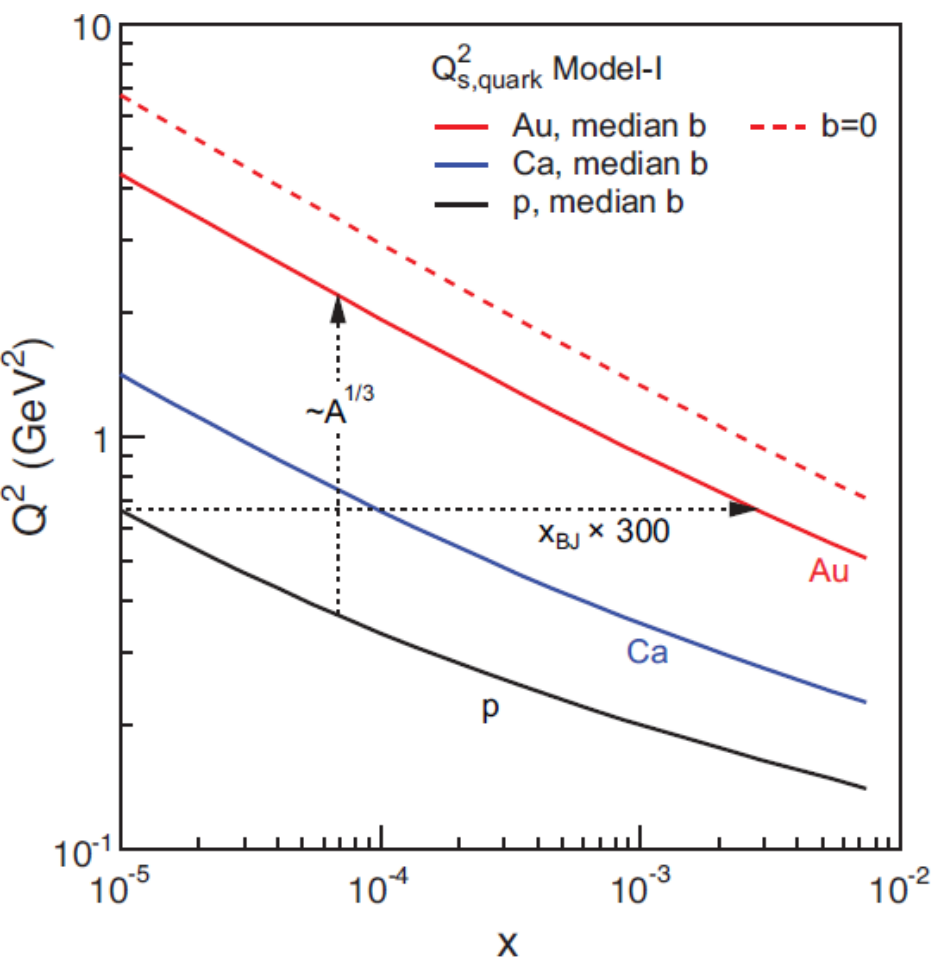
quark and gluon helicity distributions in the polarized nucleon

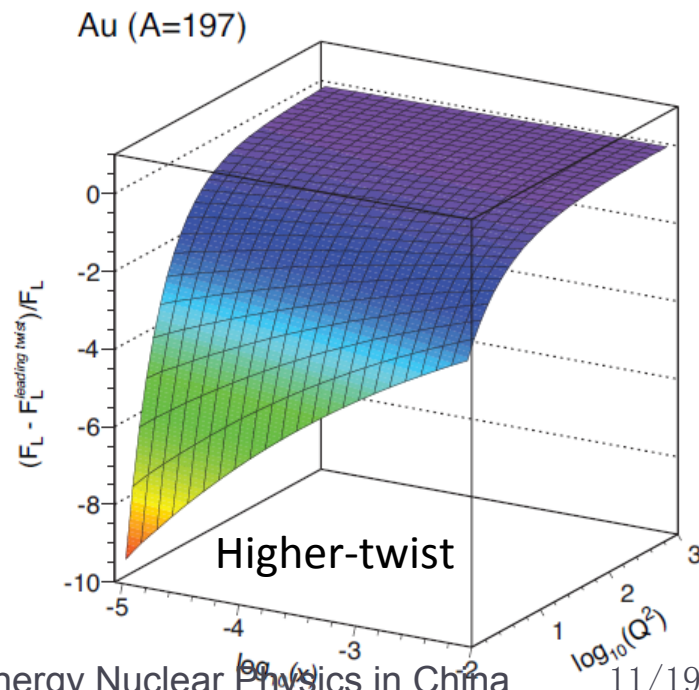
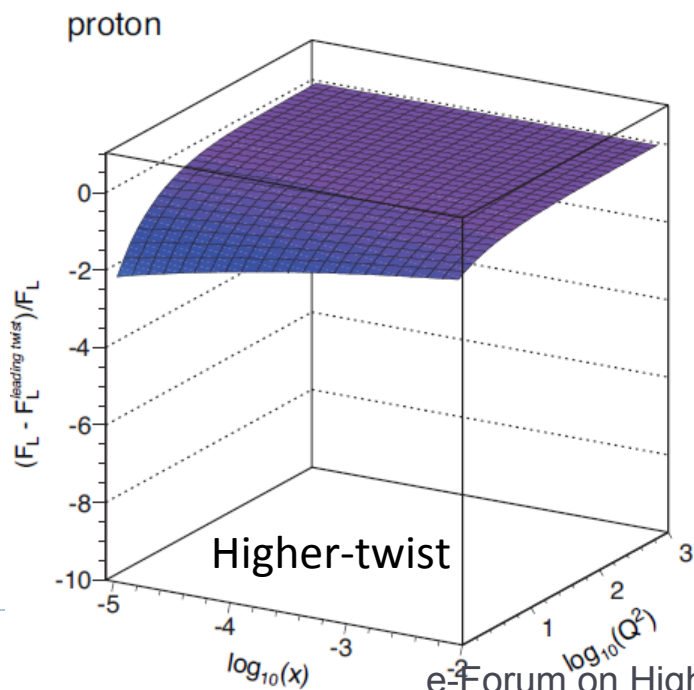
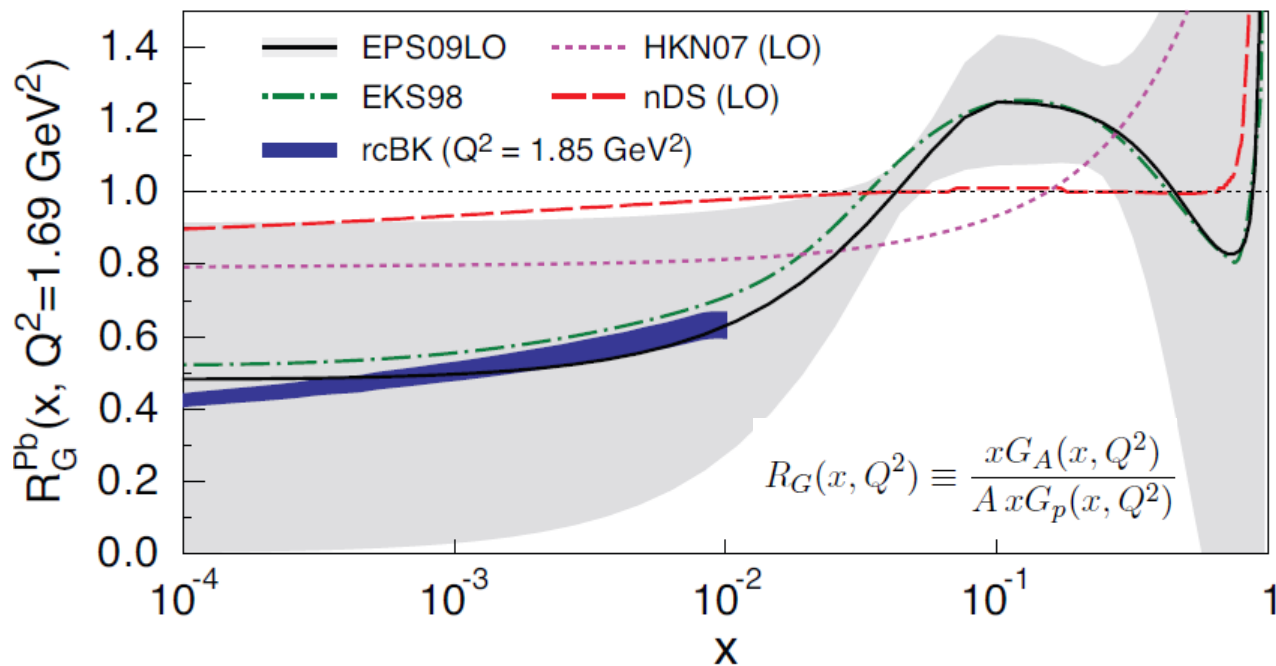


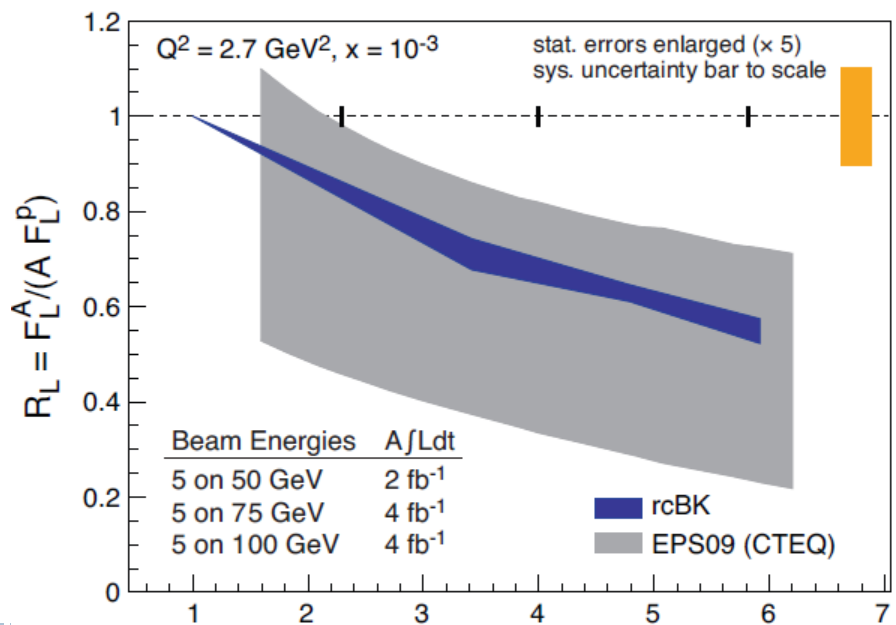
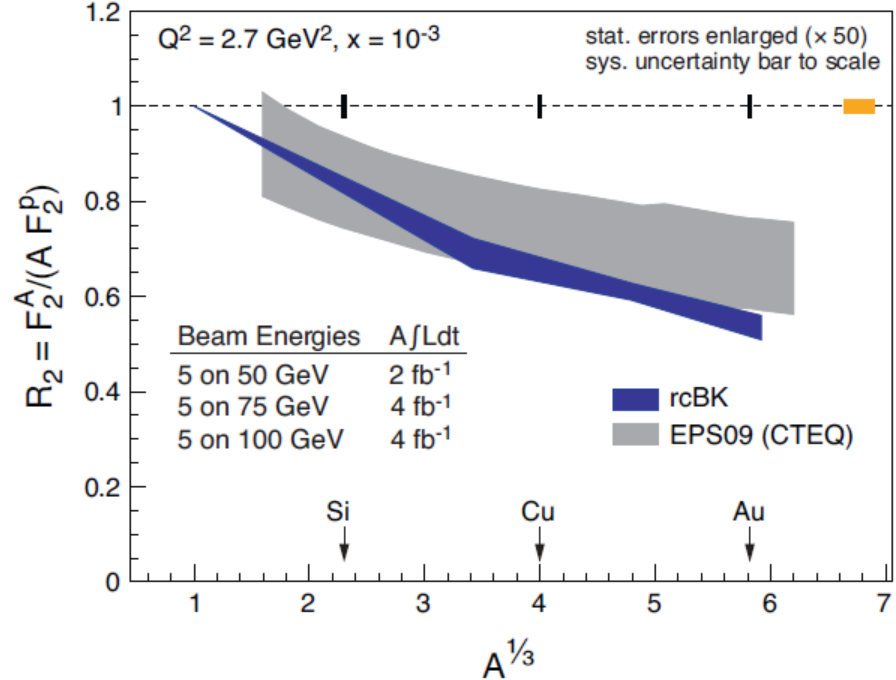
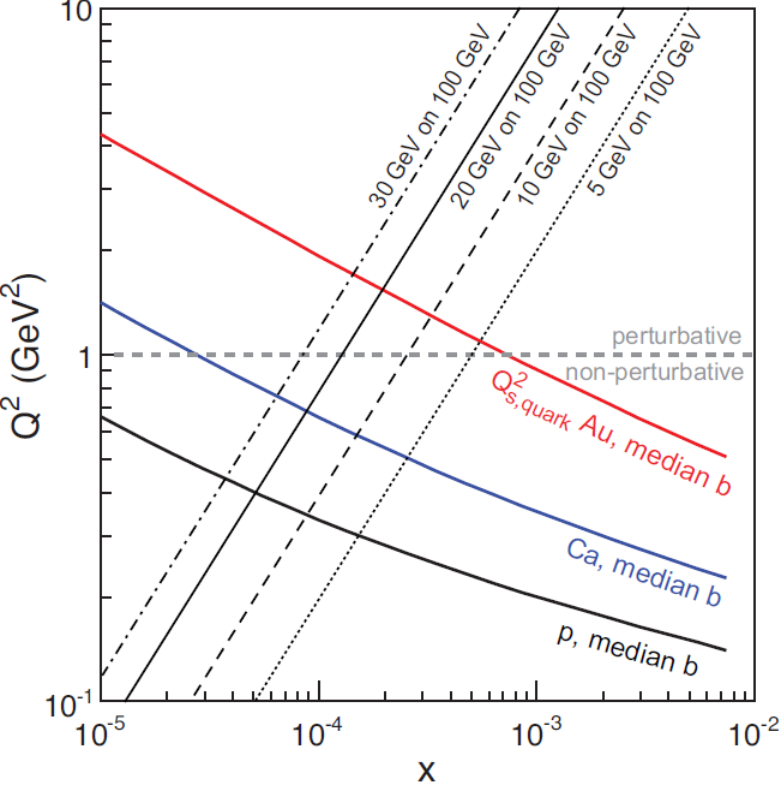
quark and gluon helicity distributions in the polarized nucleon – cntd.

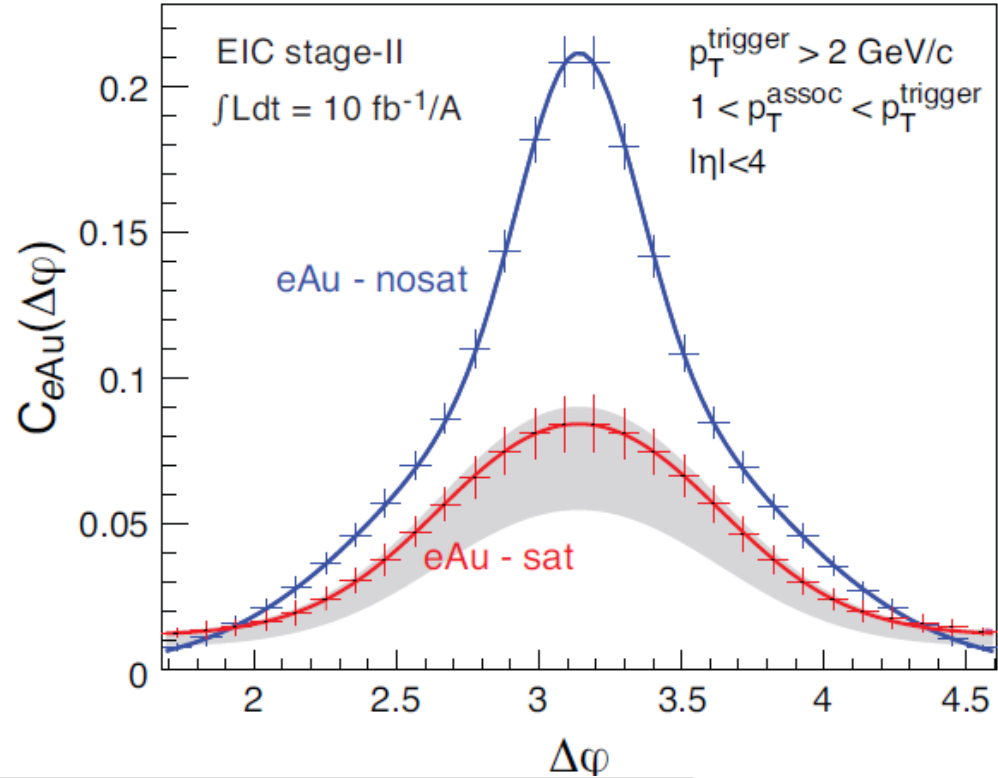
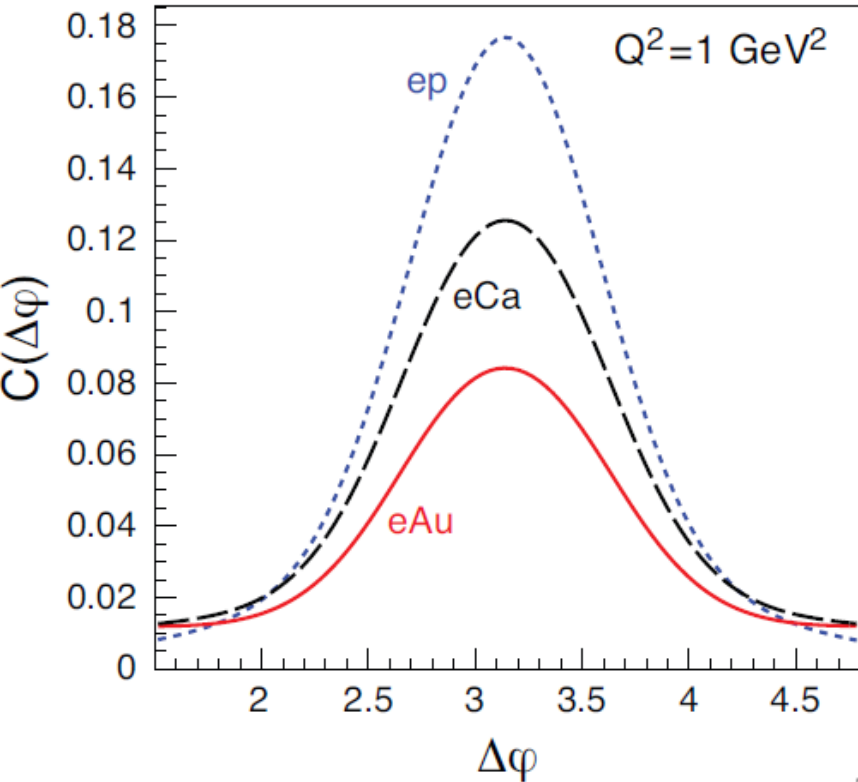




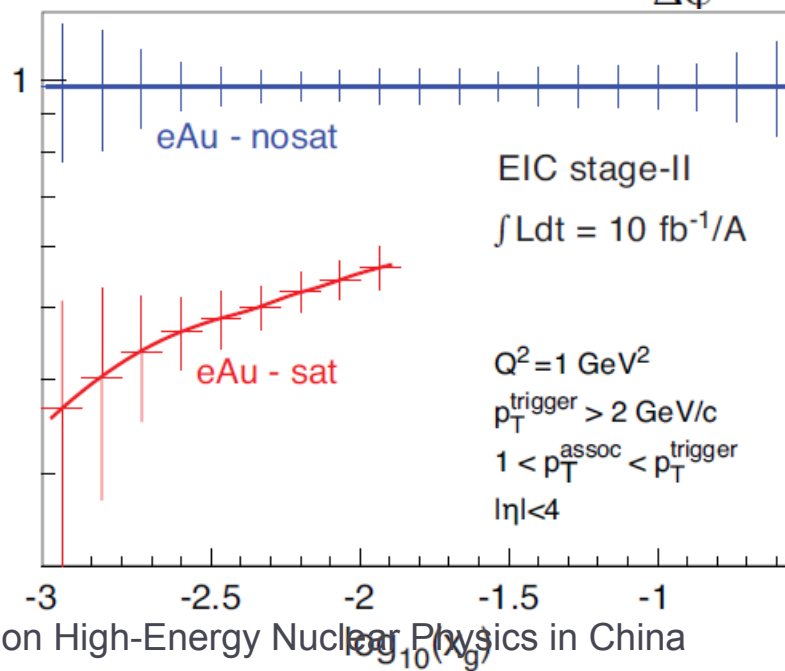


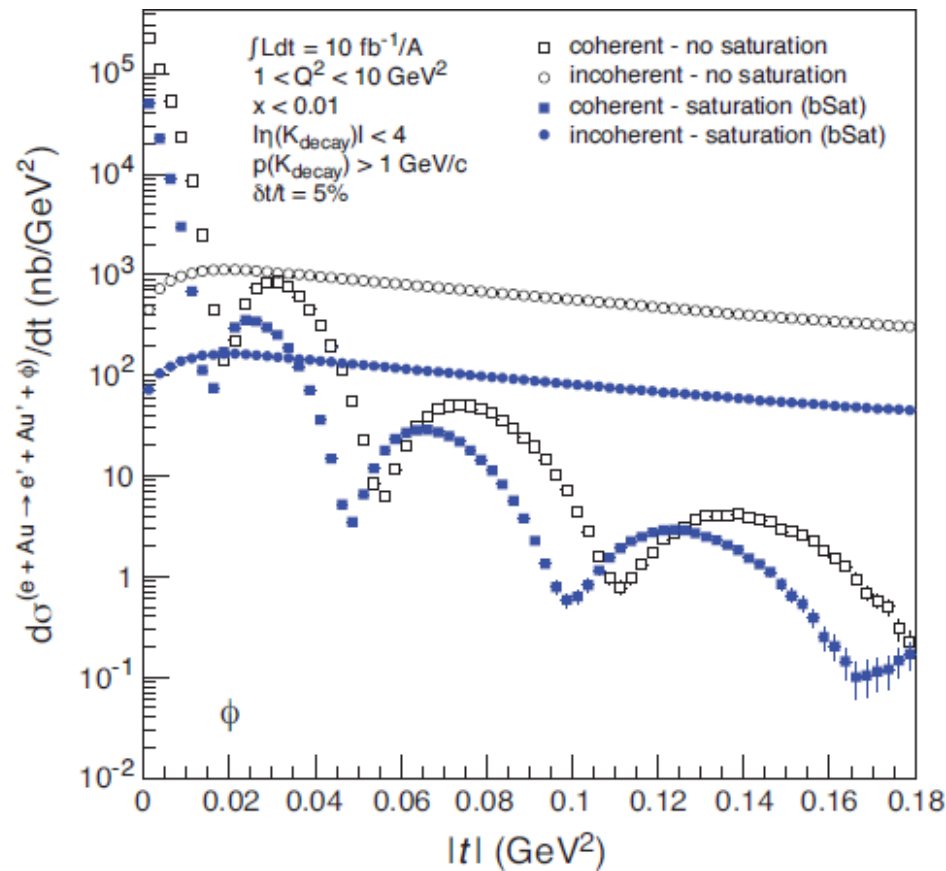
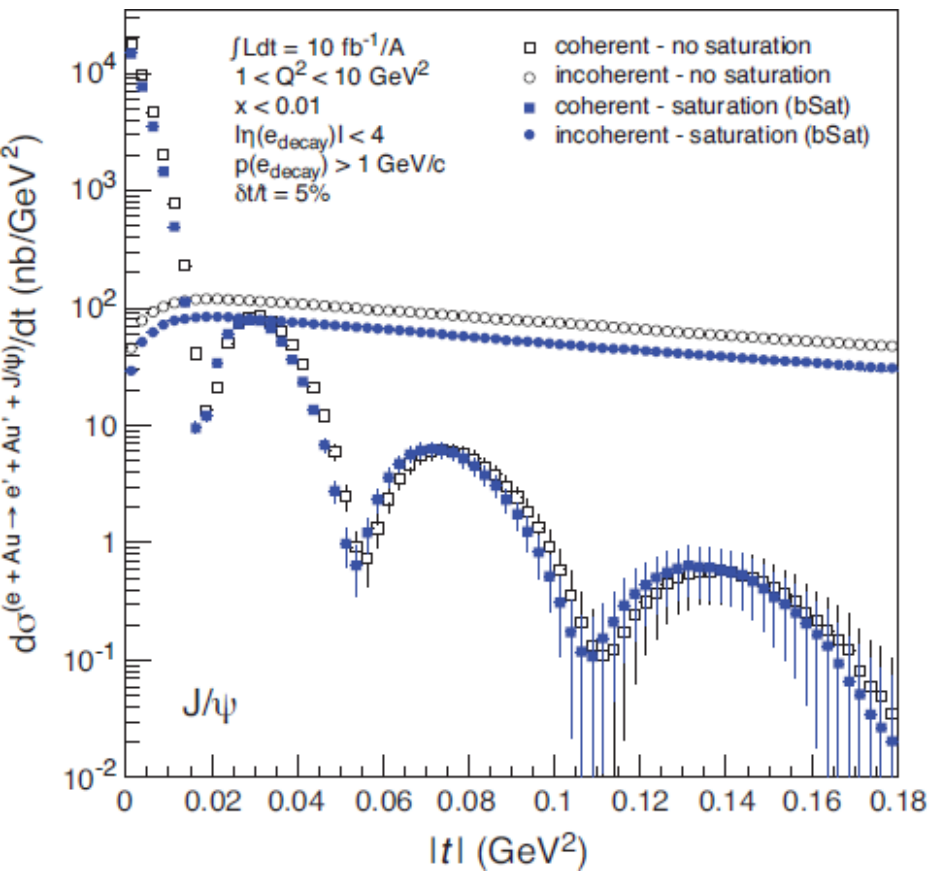






$$J_{eA} = \frac{1}{A^{1/3}} \frac{\sigma_{eA}^{\text{pair}} / \sigma_{eA}}{\sigma_{ep}^{\text{pair}} / \sigma_{ep}} J_{\text{eAu}}$$





The Distribution of Quarks and Gluons in the Nucleus

